Effect of row width and plant population density on yield and quality of maize (*Zea mays*) silage

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by

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Abstract of a thesis submitted in partial fulfilment of the requirements for the degree of Master of Agricultural Science

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The study reported in this thesis was conducted during 2015/2016 at Lincoln University, New Zealand, to investigate the effect of row width and plant population density on yield and nutritive quality of maize silage (Pioneer Hybrid P7524).

A Randomized Complete Block Design was used. The main treatments were row widths (0.76m and 0.38m) whilst the sub-treatments were intra-row spacings (0.12m, 0.18m and 0.24m), giving a total of six plant population densities (54,824, 73,099, 109,649, 146,198 and 219,298 plants/ha) with four replicates each.

The crops were harvested at 30-35% DM and ensiled in PVC type silo for 100 days. Grain, DM and stover yield per unit area increased significantly with increasing plant population due to increasing radiation interception. However, low leaf chlorophyll concentration was also found to reduce grain and DM yield in spite of high radiation interception. Also, at constant or same intra row spacing, the 0.38m row width recorded percentage grain increases of between 78.6% and 127.6% which were almost twice or more compared with the 0.76m row width. Increasing plant population also increased leaf chlorophyll concentration of plants

during the initial stages of plant growth and development. Plant population density and row width did not have any significant impact on the nutritive value of maize silage.

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Abbreviations

Abbreviation	Description	Units
ADF	Acid Detergent Fibre	%
CP	Crude Protein	%
DM	Dry matter	-
g	Gram(s)	-
iPAR	Intercepted Photosynthetically Active Radiation	MJ m^{-2}
ME	Metabolizable Energy	MJ ME/kg DM
N	Nitrogen	-
NDF	Neutral Detergent Fibre	%
NIWA	National Institute of Water and Atmospheric Research	-
NUE	Nitrogen Use Efficiency	g N/g DM
PAR	Photosynthetically Active Radiation	MJ m^{-2}
RUE	Radiation Use Efficiency	g dry matter MJ^{-1}
SPAD	Soil and Plant Analyzer Development	-
WAP	Weeks After Planting	-
WUE	Water Use Efficiency	g DM/g water
β	Fraction of PAR transmitted	-
τ	Fraction of PAR intercepted	-

CHAPTER ONE

Introduction

1.1 Background to the study

Since 1994 the New Zealand dairy industry has increased significantly with the national herd increasing from 3.8 to 6.6 million animals (Statistics New Zealand, 2014). It accounts for 7% of Gross Domestic Product (GDP) and thus can be considered as an immense contributor to the national economy (Clark *et al.,* 2007). In 2012, the industry injected NZ$ 11.6 billion as dairy export revenue into the economy (Foote *et al.,* 2015).

Dairy farmers, in an attempt to ensure continuous production and/or increase productivity, rely mainly on pasture systems where perennial ryegrass (*Lolium perenne*) forms a significant component. However, Clark *et al.* (2007) reported that a lack of cheap, highly nutritive, value feed for milk-producing cows with high genetic potential is one of the main issues currently confronting the dairy industry.

Research has indicated that high quality grass silage, when partially replaced (approximately 33% inclusion) with high quality maize silage (200-250g starch/kg DM), increases forage intake, milk yield and milk protein concentration (Fitzgerald *et al.*, 1998). Also, a high level inclusion (of approximately 67%), increases fat and protein yield as well as milk protein concentration (Fitzgerald *et al.,* 1998). This can be made possible by increasing silage production through increasing plant densities (Rutger & Crowder, 1967) without compromising quality. Meanwhile, Otegui (1997) reported barreness when maize was cultivated at 160,000 plants/ha thereby reducing the proportion of highly digestible grains in silage. Thus, under high plant population densities the quality of silage could be affected (reduced) since digestible grains contribute significantly to the nutritional value of silage.

Kishida & Ushida (1985) in a study also indicated that dry matter (DM) yield per plant was found to be high at 3,338 plants/ha and intermediate at 4,167 plants/ha plant densities. However, silage quality was not affected irrespective of plant density. Baron *et al.* (2006) also showed that plant population densities (75,000, 100,000 and 125,000 plants/ha) had a greater impact on whole plant yield than row width. According to these authors, narrow plant spacings (intra row) has a positive impact on silage yield. Also, the effect of hybrid, row spacing and plant densities on nutritive value parameters were insignificant. On the contrary, Skonieski *et al*. (2014) indicated that a narrow row spacing (40cm) increased lignin concentration, total carbohydrate and neutral detergent fibre content and decreased protein concentration and total digestible nutrients. A wider row spacing (80cm) resulted in increased protein content and quality.

In New Zealand, Thom *et al.* (1981) conducted studies on how plant population and time of harvest affected yield and quality of maize with plant populations of 85,000, 181,000 and 362,000 plants/ha, and with 75cm, 45cm and 22.5cm row widths (spacings). The study showed that high plant population densities had little effect on mineral (N, P, K, Na, Ca and Mg) concentrations. Total dry weight per plant and the weight of individual shoot components (especially leaves, stems and grain) were, however, reduced at high plant population densities. Also, dry matter yield per hectare increased with a high plant population density(i.e. 21.3, 27.4 and 36.1 tonnes/ha for 85,000, 181,000 and 362,000 plants/ha respectively) only for the first year. However, during the second year, dry matter yield was 22, 25 and 24.4 tonnes/ha for the 85,000, 181,000 and 362,000 plants/ha treatments respectively.

Grain yield decreased linearly whilst lodging increased with increasing plant populations when three maize hybrids (Pioneer 3901, PX49 & XL35) were grown at populations of

approximately 35,000, 53,000, 71,000, 88,000 and 106,000 plants/ha (Eagles, 1987). Grain yield for Pioneer 3901 and XL35 peaked and dropped at 90,000 plants/ha in the 1981-82 trials. However, only Pioneer 3901 peaked and dropped at 90,000 plants/ha in the 1983-84 trials. Stone *et al* (2000) also conducted a study using two hybrids with different maturity times (hyb. 36H36 and hyb. Raissa) at seven population densities (70, 80, 90, 100, 110, 120 and 140 thousand plants/ha) and row spacings of 25, 50 and 75cm. The study showed an inconsistent and minimal influence of row spacing on yield and quality, whilst the effect of population on yield and quality were predictable and significant. Also, the effect of row spacing (25 or 50cm) on yield and quality was extremely insignificant compared with the 75cm row width. For every additional 10,000 plants/ha population increase yield increased by 7% up to a plateau which usually occurred at 120,000 plants/ha.

Millner *et al* (2005) investigated the effect of hybrid and plant population on yield, metabolizable energy content and nitrogen percentage of forage maize using seven hybrids at 75,000, 100,000 and 140,000 plants/ha. The study showed significant hybrid differences on yield and metabolizable energy (which was not correlated with forage yield). Conversely, plant population had no effect on dry matter partitioning and forage yields declined significantly at the lowest population. George and Fletcher (2009) also investigated the impact of plant populations (65,000-190,000 plants/ha) on maize silage DM yield, quality (in terms of grain yield) and economic value and indicated that increasing plant populations increased DM yield and profitability (especially at high populations of 150,000-170,000 plants/ha). Conversely, plant population had no effect on grain yield. The optimum plant population for maize silage has been found to be between 115,000-130,000 plants/ha (Densley *et al*., 2003). However, how the different row widths and plant populations affected silage quality (in terms of crude protein, metabolizable energy, digestibility, pH, ADF and NDF) were not explored by these researchers.

1.2 Problem statement

New Zealand accounts for approximately 35% of global dairy trade. Dairy farmers in the country depend heavily on pasture systems and milk yield is strongly correlated with dry matter production. Researchers in an attempt to contribute to ensuring sustainable milk production and exports, aim at developing improved crop varieties and/or hybrids which are capable of increasing forage yield with reduced cost. Maize silage is high yielding, has a high metabolizable energy and is used in New Zealand as a low-cost source of energy by dairy farmers. Several studies have indicated that increasing plant populations increase DM yield. Villaver (1996) in a study focused on digestibility and percentage nitrogen of seven maize hybrids grown at 100, 000 plants/ha and reported no significant difference among the hybrids. Recent studies in New Zealand have also focused on maize intercrops, the optimum plant population for silage maize production and the economic returns (profitability) of plant population densities above the optimum, or the role of inoculants on the quality of pasture and maize silage (Kleinmans *et al.,* 2011) . However, the precise impact of different population densities on maize silage quality have not been fully explored, especially in the Canterbury region where approximately 17% of New Zealand's dairy industry is located. Studies conducted overseas on how row width and population density influence silage maize yield and quality have also been inconclusive (Densley *et al*., 2001).

Additionally, with increasing genetic improvement in the ability of hybrid maize to tolerate stress resulting from plant population densities it has become necessary for optimal plant densities and row widths to be reassessed by agronomists (Widdicombe & Thelen, 2002).

1.3 Aim and objectives

The purpose of this study was to evaluate the impact of row width and population density on the yield and silage quality of Pioneer Maize Hybrid P7524®. Specific objectives were to:

- ✓ Evaluate how row width and plant population density affects maize yield and silage quality.
- ✓ Examine the correlation between intercepted radiation yield/quality components.
- ✓ Examine the relationship between leaf chlorophyll content and yield/quality of maize silage.

1.3.1 Thesis structure

This thesis comprises of six (6) chapters (Fig. 1.1). Chapter 1 provides information on the role of the dairy sector in New Zealand's economy and explains how increasing forage yield (especially through increasing plant population density) contributes significantly to an increase in productivity. It also points out the knowledge gap in relation to how increasing forage yield affects silage quality especially in New Zealand.

Chapter 2 provides review of literature on the role of forage maize in the dairy sector and how row width and plant population density contribute to increasing yield are reviewed. The chapter also reviews literature on how row width and population density influence maize growth and developmental processes and their effect on dry matter accumulation. Chapter 3 outlines the trials whose data are presented in Chapter 4.

Data on how row width and plant population density affect dry matter accumulation and silage quality are presented in Chapter 4.

Chapter 5 discusses the impact of row width and plant population density on maize yield and silage quality (nutritional values) based on data presented. Chapter 6 discusses the general implications of row width and population density on maize yield and silage quality and also highlights areas for further research.

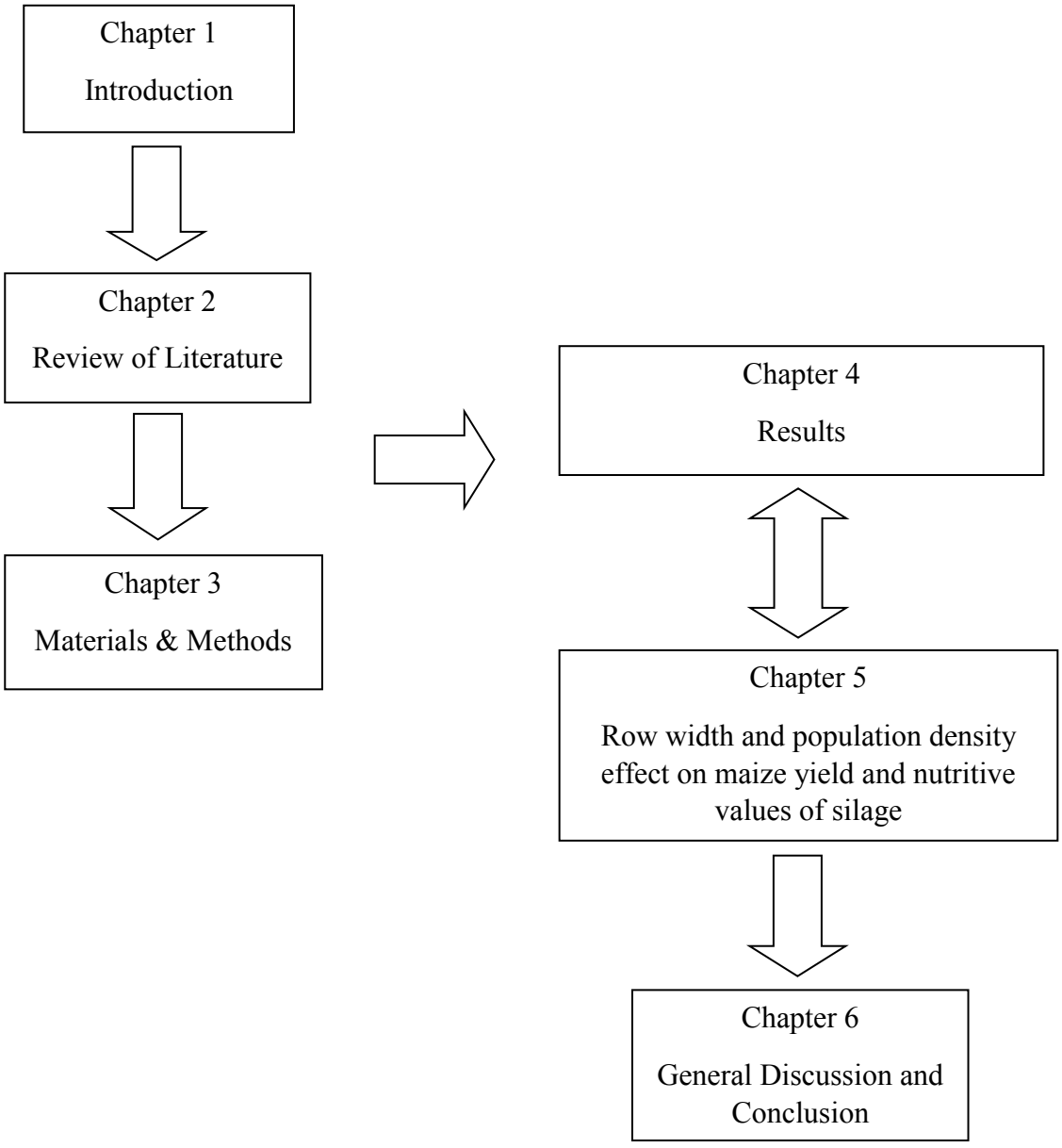

Fig.1.1: Outline of thesis structure

1.4 Delimitation and Justification

The study involved only one hybrid (Pioneer Maize Hybrid P7524) which could affect the outcome of the study and how population density could affect its yield and silage quality .

The findings should provide researchers as well as other stakeholders with information on the performance of hybrid maize silage which could lead to the development of improvement strategies for the crop. It will also provide dairy farmers with options for increasing maize silage yield and quality, to enable them to maximize milk production. With the rapid expansion of New Zealand's dairy sector, further research on factors increasing the productivity and nutritional value of maize in Canterbury farming system will also be essential.

CHAPTER TWO

Review of literature

2.1 Forage maize and its role in the New Zealand dairy industry

Dairy farming occupies 13.3% (i.e. 1.6 million hectares) of the 12 million hectares pastoral land and is three times more profitable per hectare than other pastoral land use (Dairy NZ, 2011). It plays significant role in the agriculture-dependent economy of New Zealand. It exports 95% of milk produced by NZ farmers thus, representing a quarter of all New Zealand merchandize exports (Dairy NZ, 2011). The dairy sector during the last two-three decades has attained unprecedented 18% increase with the dairy cow stocking rate increasing from 2.10 to 2.83 cows/ha (LIC, 2009) and the average herd size increasing from 450 to 730 animals (Dairy NZ, 2010). This growth of the dairy sector has made it New Zealand's major foreign exchange earner, contributing approximately NZ$ 11 billion in 2012 to the New Zealand economy (Foote *et al.,* 2015).

Dairy industry in New Zealand is mainly pasture-based with grasses, clover and brassicas forming majority of cultivated crops. Farmers also receive no subsidies from the government and this has encouraged focus on low-cost and high productivity systems (Dairy NZ, 2011). The intensification and expansion of dairying has contributed to increasing demand for high quality feed to supplement the main input of perennial rye grass (*Lolium perenne*) and white clover (*Trifolium repens* L.) (Valentine & Kemp, 2007) since perennial rye grass is estimated to have an annual genetic gain of 0.4% (Easton *et al.,* 2002) and milk production is limited by the amount of pasture available in the season (Densley *et al.*, 2001).

According to Booker (2009) the total area under maize silage production during 2008/09 season ranged between 67,000 hectares and 101,600 hectares. The dairy sector consumed 99% of

national maize silage which caused its production to increase by 20% each season due to the increasing demand for maize silage (Booker, 2009). However, majority of these farmers (56%) were buying approximately 102 tonnes dry matter (average) from off-farm. Those that grew maize silage on-farm planted an average of 4 hectares (Kolver *et al.*, 2001). Kolver *et al.* (2001) again reported that in 1999/2000 season, maize silage use increased from an average of 193 kgDM/cow (531 kgDM/ha) to 339 kgDM/cow (1,028 kgDM/ha). The increase usage resulted from the profitable dairying systems for using maize developed by farmers (van der Poel, 1996) and researchers (MacDonald, 1999).

Maize (*Zea mays* L.) under warm temperatures has high radiation use efficiency (RUE) which accounts for its high dry matter yield (Sinclair & Muchow, 1999) and a high metabolizable energy (ME) ranging from 10.3 to 11.3 MJ/kg dry matter (Millner *et al.,* 2005). Thus, it is regarded as very appropriate crop when used in a rotational pasture system. Maize when compared to brassicas (such as kale), has proven to be the most promising for breaking yield limitations associated with pasture (Duvick & Cassman, 1999) and complements brassicas. In New Zealand, dairy farmers use maize silage as a low-cost source of energy to break the feed barrier (Kolver *et al.,* 2001) and also to manage risk such that maize for grains when failed can easily be converted silage (Deane, 1999; MacDonald, 1999). Kolver *et al.* (2001) further indicated that the per hectare milk solids (78g milksolids/kg DM) and days-in-milk production could be increase under high inputs of maize silage and increased stocking rate. Similarly, Densley *et al.* (2001) also demonstrated that the duration of lactation and amount of milk solids (up to 170g /kg DM maize silage fed) produced increased, especially when silage was used for autumn feeding. However, both authors were silent on the breeds of cattle used in their review. The average yield of maize silage (20-25 t DM/ha) has tripled in New Zealand over the last 40 years whilst pasture yields has remained relatively stable and thus maize silage can

be used to overcome feed shortage during summer (Densley *et al.,* 2001). According to Deane (1999), average annual pasture yield (15 t DM/ha) has not increased significantly over the last 40 years.

The average dry matter yield of pasture per hectare increased by 1.9 tonnes when maize silage was included in pasture renovation programmes (Densley *et al.,* 2001). Maize can also grow deep (150-180cm) into the soil (Grignani *et al.*, 2007) which enhances the uptake of nutrients from depths 2-3 times more than most C3 pasture grasses (Kristensen & Thorup-Kristensen, 2004). Maize when compared to pasture is more responsive to N and has high nitrogen use efficiency (NUE) (Williams, Densley & Edmeades *et al*., 2010). Thus, it helps in minimising environmental problems associated with excessive N use in pasture systems (Williams *et al.,* 2010) when farmers, in an attempt to increase dry matter production by 40%, apply high levels of N (approximately 350-500 kg N ha^{-1} $annum^{-1}$) (Andrews *et al*., 2007). Maize is also known to have low crude protein level (7-8%) (Mahanna, 2000) and thus, when used to supplement high protein pasture helps in reducing the protein content of diets and the release of N by dairy livestock (Williams *et al.,* 2010; Kebreab *et al.,* 2001). According to Ledgard (2006) when used for feeding cows, maize silage can reduce the N concentration of urine by 70%. Woodward (2002) also reported that the methane output of cows per unit total dry matter intake for cows partly-fed with maize silage (60% pasture and 40% maize silage) was found to be lower than those fed with pasture only (i.e. 20.3g CH_4/kgDM compared with 23.4g CH_4/kgDM). However, when the proportion of maize silage increases in a pasture-based diet for lactating dairy cows, methane emissions also increase (Waugh *et al.,* 2005).

In pasture renewal programmes, pest cycles (such as Clover Root Weevil and nematodes) are broken down when maize silage is included (Eerens *et al.,* 2005). Also, the level of weeds

and carryover ryegrass seeds are reduced and pasture persistence is improved (Densley *et al.,* 2011). Grazing pressure is also reduced when silage maize is used to substitute pasture.

2.2 Row width and its impact on the yield of maize.

Plant population density generally puts pressure on the growth and yield of maize (*Zea mays* L.) (Tetio-Kagho & Gardner, 1987; Porter *et al.,* 1996) due to competition among the crops for resources such as water, nutrients and sunlight. However, maize breeders over the years have focused on stabilizing the performance of maize under various stresses such as high population densities, drought, salinity and infertile soils (Campos *et al.,* 2006). This has led to increases in yield over the past three decades, mainly as a result of an increase in stress tolerance rather than genetic yield potential (Duvick & Cassman, 1999). Almedia *et al.* (2000) indicated that maize hybrids released in the 1990s, when compared to genotypes released before that time, have greater tolerance to higher plant population densities. These improvements in breeding programmes towards stress tolerance have necessitated the review of row width (spacing) of maize plants over the years (Widdicombe & Thelen, 2002).

Cardwell (1982) indicated that the 1930s standard row width (107cm) was reduced to 90cm in the late 1970s. In recent years, maize is either sown in wide row widths (76cm) or narrow row widths (38cm), but the trend has been on narrowing the row width and increasing the plant population (Porter *et al.,* 1996). However, narrow row widths give varying yield responses such that to some researchers it gave a yield increase over wider row width, whilst others found the opposite. Porter *et al.* (1996) observed average yield advantage of 7.2% for 25cm and 50cm row widths compared with 76cm row width. Milk and dry matter yield of maize sown at 38cm was 17.7 and 22.4 t ha^{-1} respectively compared to 16.8 and 20.8 t ha^{-1} respectively for 76cm

spacing (Cox & Cherney, 2001). In a study by Cox *et al.* (1998), the average silage maize yield was 55.8 t ha^{-1} at 38cm row width and 53.6 t ha^{-1} at 76cm row width. Brown *et al.* (1970) similarly found that yields of irrigated corn were higher in 51cm rows than 102cm rows. Even under no irrigation, "Pioneer 309 B" yielded more grains at a narrower spacing (51cm) than at a wider row spacing (102cm) and recorded a similar trend for "DeKalb XL 65" under irrigation. However, "DeKalb XL 65"under no irrigation yielded similar grains. Widdiecombe and Thelen (2002) observed similar output in terms of dry matter yield for forage and dual purpose hybrids (1.2 and 1.0 t ha^{-1}, respectively) when the row width was reduced from 76cm to 38cm and indicated that the narrower row width had no impact on the quality of forage in terms of crude protein, digestibility, acid detergent fibre and neutral detergent fibre. Narrow row widths (55cm) were also found to have significantly reduced weed density and dry weight by 9% and 34% respectively compared with 75cm row widths (Maqbool *et al*., 2006). On the contrary, trials conducted by Farnham (2002) recorded a higher yield (11.6 t ha^{-1}) for maize cultivated at 76cm compared to the 11.4 t ha^{-1} for crops grown at 38cm row widths. In the United States where narrow row width is influenced by the size of the power unit used to cultivate and harvest corn, the narrow rows are normally 20 inches (50 cm) to match the row width of soybean so that both can be planted and harvested at the same time (Lauer, 1996).

In New Zealand, maize was initially sown at approximately 100cm in the early 1900s to allow the real horse power needed to draw tillage implements (Stone *et al.,* 2000) until the early 1960s when the row width was reduced to 90cm for crops which were traditionally sown at 48,000 plants/ha (Graham, 1967). According to Douglas *et al.* (1982) the exact plant population at which grain yield could be maximized under high yielding conditions was not clearly indicated in early studies. However, later research in the 1960s showed that under favourable moisture conditions, grain yield increases ranging from 21-37% could be attained at plant

populations up to 90,000 plants/ha in 76cm rows (Douglas *et al*., 1971) which was beyond the optimum for full season maize hybrids in other parts of the world (Downey, 1971). Grain yield increased between 8 and 13% when maize was sown at 38cm compared to those with 76cm row spacing (Douglas *et al.,* 1971).

Row width when reduced helps in minimizing crops competition with weeds for water and nutrients (Olson and Sander, 1988; Porter *et al*., 1996) due to low transmittance of solar radiation to the soil surface (Johnson *et al.*, 1998; Teasdale, 1995). According to Bullock *et al.,* 1988) the growth of maize is enhanced in the early part of the growing season leading to increasing radiation interception and radiation use efficiency, reduction in light transmittance through the canopy (McLachlan *et al*.,1993) and increasing grain yield (Westgate *et al*., 1997). Karlen and Camp (1985) also indicated that rapid canopy closure resulting due to narrow row width helps in reducing water lost through evaporation, runoff and soil erosion (Sangoi *et al*., 1998).

2.3 Phenology of Maize

Phenology is defined as the initiation, differentiation, expansion and loss of plant structures (Hay & Porter, 2006; Bonhomme, 2000a). The timing of these developmental events varies with environment and genotype or inherent maturity of the plant material (Birch *et al.,* 2003). Maize, like any annual crop, undergoes five main developmental phases, namely; germination, vegetative growth, reproductive growth, physiological maturity (Angus *et al.,* 1981) and senescence (Thomas & Stoddart, 1980) with each phase lasting within a specific time frame (Thornley & France, 2007).

2.3.1 Germination and Emergence

Maize seed germinates under favourable conditions, mainly temperature (which affects significantly seed moisture content especially at the initiation of radicle growth), moisture and oxygen (Blacklow, 1972). Studies have indicated that above the critical threshold for vegetative growth (8°C) (Birch *et al.,* 1999) the pre-emergence growth rate of maize increases linearly with temperature (Weaich *et al.,* 1996; Kiniry *et al*., 1991). Thus, water imbibition also increases as rate of metabolic activities increase. A study by Blacklow (1972) showed that seed moisture content at initiation of radicle was 57% at 30°C and increased to as much as 75% under less favourable temperature (12°C). When nitrogen and moisture are non-limiting, crop development is driven mainly by temperature (Forcella *et al.,* 2000) and affects every single phase of crop development (Warrington & Kanemasu, 1983a). Metabolic activity in the seed is initiated when cells are well hydrated (Hanway, 1963). The period of germination ends when the radicle emerges from the seed embryo and the plant is said to have emerged when the mesocotyl and coleoptiles extend above the soil (Hanway, 1963).

2.3.2 Vegetative growth

2.3.2.1 Leaf initiation and expansion

Leaves are "plant antennae" mostly green in colour (due to the presence of chlorophyll) and are specialized for capturing photosynthetically active radiation and for removing excess water to reduce plant temperature and absorbing carbon dioxide (van Volkenburgh, 1999). Maize seed at physiological maturity has five embryonic leaves (Duncan, 1975) and leaf primordia of the apical meristem initiate leaf production (Dale, 1982; van Volkenburgh, 1999). In maize the

leaf lamina grow with a clear vascular pattern to an appreciable length before forming the sheath (van Volkenburgh, 1999). The leaf tip, for ease of observation, is considered to have appeared when the leaf collar (discoloured line between the leaf blade and leaf sheath) is visible (Fletcher *et al.,* 2008a) and fully expanded when and its ligule is seen above the whorl of preceeding leaf (Muchow & Carberry, 1989). According to Warrington and Kanemasu (1983b), thermal time between emergence of leaf tips is more uniform than successive appearance of leaf ligule.

The period between sowing and silking is associated with the number of leaves per plant and rate of leaf appearance, which are affected by genotype (Russell and Stuber, 1983) and temperature (Tollenaar *et al.,* 1979). Ritchie & NeSmith (1991) indicated that the rate of development is linearly related with temperature within the critical threshold and optimum temperature range. Warrington and Kanemasu (1983b) also indicated that both leaf initiation and rate of appearance increase with increasing photoperiod. Increasing photoperiod increases leaf number (Birch *et al.,* 1998; Coligado & Brown, 1974) as well as vegetative growth and development prior to tassel initiation (Hunter *et al.,* 1974). Leaf appearance ceases when the apical meristem changes to inflorescence (Irish & Jegla, 1997) and the total leaf number prior to tassling may range from between 16 and 22 (Russell & Stuber, 1983). However, it can be reduced by short-day growing conditions (Hanway & Richie, 1985). The thermal time interval between the appearance of successive leaf tips is defined as the phyllochron (McMaster & Wilhelm, 1995). The process of cell expansion accounts for the surface area of a mature leaf (van Volkenburgh, 1999). However, differences in leaf size are as a result of the number of cells and/or cell size (Granier & Tardieu, 1998).

2.3.2.2 Canopy development

A canopy represents the surface area of a crop exposed to the aerial environment (Zur *et al.,* 1989). According to Song *et al.* (2016) lamina and sheath lengths increase in lower phytomer (consisting of an internode with axillary bud at the bottom and a node, a leaf sheath and lamina at the top) but decrease in upper phytomers which influence canopy structure by affecting mainly the quantity and quality of intercepted radiation (Tetio-Kagho & Gardner, 1987; Andrade *et al.,* 1993; Maddonni *et al.,* 2001). In maize, the leaf shape (narrow leaves) allows more incident light to penetrate deeper into the lower canopy for photosynthesis (Song *et al.,* 2016). Generally, plant population affects canopy development due to the increased sensitivity of lamina extension to increasing interplant competition compared with sheath extension. A study by Song *et al.* (2016) indicated that increased plant density promoted lamina extension in lower phytomers while lamina extension in upper phytomers reduced. Lamina width and stem diameter reduce due to smaller growth rate in response to an increased plant population. However, in lower canopies, internode and leaf length lift up leaves in the lower to intercept more light (Song *et al.,* 2016).

2.3.2.3 Stem elongation

The embryonic stem of maize is made up of a meristematic cone containing approximately 5-7 leaf primordia with no distinction of internodes (Martin, 1988). The first internode is formed below the coleoptile and elongates rapidly leading to emergence (Fournier & Andrieu, 2000). According to Parvez *et al.* (1998) elongation of the coleoptile internode ceases at emergence, a phenomenon which is triggered by a light signal. Higher internodes originate from intercalary meristems which are in the lower half of the discs of insertion of primordia

(Sharman, 1942). Intercalary growth occurs at the apex after transition to the reproductive phase (Martin, 1988). Before this transition, the whole stem (apical cone) elongates at a very slow rate as a single entity (Siemer *et al.,* 1969). After tassel initiation, the stem elongates at a slightly faster rate and from ear initiation onwards it elongates rapidly up to anthesis and silking (Siemer *et al.,* 1969). Plant height in the pre-flowering period (marked by rapid elongation) is often measured as the height from the soil surface to the highest exposed leaf tip and is linearly related to phyllochron (Robertson, 1994).

2.3.3 Reproductive growth of maize

2.3.3.1 Inflorescence

The transition from vegetative to reproductive development occurs at a leaf stage which numerically is equal to 50% of the final leaf number (Tollenaar & Hunter, 1983). Floral maturity (anthesis and silking) in maize marks the start of the reproductive phase and the end of the vegetative growth (Bolanos & Edmeades, 1996). In maize, anthesis preceeds silking by a short duration. The tassel (male inflorescence) is a branched flower found at the tip of the main stem, consisting of the rachis (central spike) and approximately 10-50 lateral branches (Cheng & Pareddy, 1994). Tassel initiation occurs at approximately one-third of the time between sowing and anthesis when calculated either on the basis of degree-days (heat sums) or calendar days (Warrington & Kanemasu, 1983a). However, the synchrony of anthesis and silking for floret fertilization is very sensitive to environmental stress (Borras *et al.,* 2007) and the anthesis-silking interval is affected by plant density (Sarjamei *et al.,* 2014). In a study conducted by Jacobs and Pearsons (1991), increasing the plant population from 5 plants/m^2 to 20 plants/m^2 increased

asynchronous flowering and reduced grain yield per plant (but not per hectare) by 47%. Days to 50% silking also increase with increasing plant density (Amanullah *et al.,* 2009) and according to Sangoi (2000), silking (growth of ear primordia) is delayed by 2-3 days as the population increases. On the whole, as plant density increases the number of days to silking is increased while the time from silking to physiological maturity is decreased and time to anthesis is little affected (Dawadi & Sah, 2012).

2.3.3.2 Ear development

Ear development is a recurring process of meristem initiation and organ differentiation starting with the flower meristem and ending with spikelet development (Lee *et al.,* 2013). An ear capable of producing matured kernels is developed from one or several axillary buds which are covered with about 8-14 modified leaves (the husk) and a prophyll (a leaf formed at the base a shoot or pedicel, usually smaller than the standard leaf) and has a thick axis (the cob) which produces multiple rows of paired spikelets (Cheng & Pareddy, 1994). According to Duncan (1975) up to eight potential ears develop initially, but only one to two top ears become dominant and progress, with further development mainly as a result of nutrient availability and the plant population. Plant population density affects the light environment of maize such that under unfavourable light environments individual plants abort ears three-four days before silking. This continues until approximately three days after silking, signifying that ear development is a critical period for light competition (Prine, 1971). Increasing the plant population also reduces kernel number per plant. In a study conducted by Otegui (1997), a plant population density of 16 plants/m^2 resulted in barreness due to increased number of unpollinated ovaries and kernel

abortion. Likewise, spikelet abortion did not occur except at a population density of two plants/m^2.

2.4 Dry matter accumulation

The process of photosynthesis in higher plants generates carbon which is used in the synthesis of carbohydrate (Huber *et al*., 1992). According to Gordon (1985) the products of photosynthesis may be used in the leaf, or be transported to other parts of the plant for use. Plant dry matter accumulation is affected by resource capture and subsequent utilization (Tollenaar & Dwyer, 1999) and generally increases with increasing cumulative solar interception (Monteith, 1977; Russell *et al.,* 1989). Dry matter yield has also been found to be affected by plant population density (Ferreira *et al.,* 2014; Sadeghi, 2013). Thom *et al.* (1981) recommended that maize should be grown at a low plant population since high grain content is considered an important determinant of the feeding value of maize silage for cattle (Montgomery *et al.,* 1974). However, when the plant population is increased to maximize total dry matter yield, grain dry matter yield is reduced (Bunting, 1973; Douglas & Dyson, 1972) due to the parabolic and asymptotic relationship of grain DM and total DM yield with plant population (Downey, 1971; Bunting, 1971).

2.4.1 Radiation Use Efficiency (RUE)

Maize growth and yield is affected by intercepted incident radiation (Maddonni & Otegui, 1996; Pommel *et al.,* 2001) as well as its composition, such as Red (R) and Far Red (FR) (Maddonni *et al.,* 2002; Markham & Stoltenberg, 2001). Though light interception is not affected

by maize row spacing, it is influenced by plant population density (Westgate *et al.,* 1997) and N rate (Dahmardeh, 2011). According to Toler *et al.* (2013) light interception for high density crops increased by 15% compared to low density crops. When water and nutrients are non-limiting (Otegui & Andrade, 2000) kernel number per plant is related to the amount of intercepted photosynthetically active radiation (Otegui, 1997). Warren (1967) defined RUE as the ratio of accumulated biomass to radiation interception within a specific time frame. It is affected by light (Villalobos *et al.,* 1992; Connor & Sadras, 1992), temperature (McMurtrie & Wang, 1993), vapour pressure deficit (Stockle & Kiniry, 1990; Landsberg & Hingston, 1996) and other plant related factors. Maize when compared to other crops from the Poaceae family, has the highest RUE (3.5g/MJ iPAR) (Kiniry *et al.,* 1989). The efficient use of intercepted radiation (which is not affected by plant population) (Stone *et al.,* 1998) indicates the extent of biomass production (Barker & Ort, 1992; Tollenaar & Aguilera, 1992). RUE is decreased when leaf area index (LAI) is reduced due to the exposure of a significant proportion of crop leaf area to radiation that approaches photosynthetic light saturation (Sinclair & Horie, 1989). However, light saturation is rare among C4 crops but much more of a factor for C3 crops.

2.4.2 Nitrogen Use Efficiency (NUE)

The main soil nutrient limiting crop growth globally is nitrogen (Raven *et al.,* 2004a). It forms part of chlorophyll, growth hormones, RNA, DNA and plant proteins (Andrews *et al.*, 2013) and mainly affects leaf area expansion and senescence (Li *et al.,* 2006). Nitrogen Use Efficiency (NUE) is the output of N uptake efficiency (which is the ability of crops to take up N from the soil) (Burns, 2006), and use efficiency of the absorbed N (that is the efficiency with which crops use the absorbed N to grow and give yield) (Schenk, 2006). Thus, NUE is the g DM

produced per g nitrogen absorbed by plant. It may also be expressed as grain yield per unit of available nitrogen (van Beem & Smith, 1997). In cereals, NUE hardly exceeds 50% under field conditions. It varies from 25-34%, with maize being no exception (Mosier, 2002; Raun & Johnson, 1998). Under various environments, predicting NUE for maize is difficult due to the possibility of significant interactions between management practices such as plant density and N fertilization (Ciampitti & Vyn, 2011). Magen and Nosov (2008) indicated that a 1% increase in NUE is worth as much as US$ 234,000,000. In a study conducted by Muchow and Davis (1988), RUE increased with higher rates of N applied and maximum RUE was greater in maize than in sorghum. Thus, maize when compared with sorghum is more responsive to N, leading to higher NUE, averaging 55kg DM/kg N applied for the initial 50kg N/ha applied (Williams *et al.,* 2010). Plant population density affects the ratio of total above ground N content to green area index such that the ratio decreases with increasing plant densities (Barbieri *et al.,* 2006). The NUE of maize increases with narrow row spacings (12-15%) which is often expressed as dry matter or grain yield per unit of available N due to the increased recovery efficiency (Barbieri *et al.,* 2006).

2.4.3 Water Use Efficiency (WUE)

According to Fitter and Hay (2002) Water Use Efficiency is the gCO_2 fixed per gH_2O lost. Alternatively, WUE may be defined from an agronomy point of view as the biomass accumulation (which is often expressed as crop grain yield or total crop biomass) per unit area divided by water consumed (expressed as evapotranspiration or transpiration) to produce the yield (Sinclair *et al.,* 1984). Under fertile soil conditions, water deficit severely affects the productivity of crops, with maize being no exception (Boyer, 1982). It is necessary for every developmental phase of plants. However, less than 20% of water supplied is utilized effectively

by plants (Saeed, 1994). Maize, when compared to perennial rye grass, is twice as water efficient on an annual basis and three times higher on a summer seasonal basis (Neat *et al.,* 2007). It produces approximately 34-62 kg DM/mm of water (Williams *et al.,* 2010). WUE is affected by plant density, row spacing and their interactions. Yada (2011) observed highest water use at a plant density of 125 000 plants/ha whilst biomass WUE was highest at a row spacing of 0.45m with a plant density of 125 000 plants/ha. Increasing plant density increased the WUE of maize by 24% under irrigation and reduced it by 17% under rainfed conditions (Ogola *et al.,* 2005).

2.5 Maize silage

Maize, one of the most important crops worldwide, is grown in the tropics mainly for grain whereas within Europe approximately only 50% of the crop is for grain (Crowley, 1998). The remaining 50% is grown for forage in more temperate regions. Maize is capable of increasing the forage intake of livestock (sheep and cattle) and producing higher live weight gains than other consumed forages. Maize is therefore attractive as preserved forage (e.g. silage) due to its inherent quality (Crowley, 1998).

Silage is the feedstuff produced when a crop, forage or agricultural by-product with more than 50% moisture content is fermented (Bolsen *et al.,* 1996). The ensilability of a crop is affected by its dry matter and sugar content as well as its buffering capacity. Maize is "nearly perfect" in terms of its ensilability because it satisfies perfectly well these conditions. Lucerne (alfalfa) on the other hand, is the most difficult crop to ensile (Bolsen *et al.,* 1996). Silage constitutes an important feed supplement in the diary sector of New Zealand, despite variations in terms of quality (Kleinmans *et al.,* 2011). It provides a low cost source of energy in the form

of starch and fibre which complements pasture well for most parts of the year (Kolver *et al.,* 2001). Since the 1950s, the amount of silage made in developed countries including New Zealand has increased steadily at the expense of hay (Wilkinson & Stark, 1992)

2.5.1 Features of good quality silage.

The nutritive value of maize silage is mainly dependent on the cob: stover ratio (Kolver *et al.,* 2001). It is influenced by plant population density such that under high population densities, number of kernels per ear decrease (Prine, 1971) and number of unpollinated ovaries and kernel abortion increase, resulting into barrenness (Otegui, 1997). Maize kernels (grains) when included in silage affects significantly the nutritive components (starch content, metabolizable energy and protein) of the feed and as well as milk properties (such as milk protein and cholestrol) . Ideally, good quality silage should have high metabolizable energy, protein and starch with lower levels of fibre. Quality can be maintained over a period under good management system (especially when the pH and ammonia nitrogen content are low and lactic acid content is high). Table 2.1 below shows nutritive value estimates for good quality maize silage.

Table 2.1: Nutritive value estimates for good quality maize silage

	Nutritive value estimate
Dry matter (%)	28 – 35
Energy (MJME/kg DM)	10.8+
Protein (%)	7 – 8
Degradable protein (% protein)	65 – 70
Undegradable protein (% protein)	27 – 31
Soluble protein (% protein)	< 50
Neutral Detergent Fibre (NDF) (%)	38 – 45
Acid Detergent Fibre (ADF) (%)	23 – 28
Soluble Carbohydrate (%)	38 – 50
Fat (%)	3 – 5
pH	3.8 – 4.5
Lactic acid (%)	4 – 5
Ammonia nitrogen (% total N)	< 5

Source: Adapted from Mahanna, 2000

2.5.2 The ensiling process.

Ensiling is the process of fermenting crops (Bolsen *et al.,* 1996). During the process, epiphytic lactic acid bacteria (LAB) convert water-soluble carbohydrates (WSC) in the plant to lactic acid and to a smaller extent acetic acid (Kleinmans *et al.,* 2011). This leads to a reduction in pH of the ensiling material due to the production of acid and the inhibition of destructive

micro-organisms (Oude Elferink *et al.,* 1999). However, if air penetrates into the silage yeast development may occur leading to increased temperature, mould development and subsequent dry matter and feed quality losses (Kung, 2010). The ensiling process may be divided into five (5) phases (Adesogan & Newman, 2014):

Phase 1: This phase also known as the **Aerobic phase** commences from the time of harvest to when oxygen is completely depleted from the sealed silo. Plant enzymes and aerobic bacteria cause nutrient losses by degrading plant proteins into amino acid, ammonia and to a lesser extent peptides and amides (McDonald *et al.,* 1991) and converting sugars into carbon dioxide and water and generating heat due to continuous respiration. This process may last for up to 48 hours in poorly made silages but ideally takes a few hours (Bolsen *et al.,* 1996).

Phase 2: The **Lag phase** begins after oxygen is completely utilized. Anaerobic bacteria begin to convert plant sugars into nitrogenous compounds, alcohols, carbon dioxide and organic acids (which reduce the silage pH to 5). Clostridial activities may occur at this when moisture content is high and the pH drops slowly (Adesogan & Newman, 2014).

Phase 3: This phase also known as the **Fermentation phase** and can last for 3 days – 4 weeks. Lactic acid bacteria (LAB) dominate the fermentation at this stage (once the pH falls below 5) and reduce the pH further to approximately 4 (in well-made silages) or 4.5 in haylages (round-bale silage). Lactic acid is more effective at reducing the pH than other organic acids. Thus, homolactic LAB (e.g. *Lactobacillus acidophilus, L. cornyformis, L. plantarum, L. salivarus, Lactococcus lactis* and *Streptococcus bovis*) which produce lactic acid from fermenting glucose and other 6-carbon sugars are more efficient at causing a fast pH drop and preserving nutrients than heterolactic LAB (e.g. *Lactobacillus brevis, L. fermentum, L. viridescens* and *Leuconostoc*

mesenteroides) which produce acetic acid, ethanol and carbon dioxide in addition to lactic acid (McDonald *et al.,* 1991; Bolsen *et al.,* 1996).

Phase 4: At the **Stable phase**, pH is ≤ 4 and the growth of undesirable microbes is prevented. The silage quality can be maintained so long as air does not penetrate into the silo or clamp.

Phase 5: Once aerobic conditions are restored during feeding out, air revives all fungi (moulds and yeasts) which remained dormant during the process of fermentation. The fungi use lactic acid, sugars and other nutrients for growth and produce carbon dioxide and heat (which when in excess denatures proteins and other nutrients) (Adesogan & Newman, 2014).

2.5.3 Factors affecting maize silage quality.

Maize silage in recent years is becoming more popular as a forage among dairy farmers in different parts of the world. It is high yielding, has high digestibility and energy content and very easy to ensile (Muck, 1988). The quality is influenced by several factors mainly biological (plant respiration, aerobic microbial activity, clostridia activity, plant maturity at harvest and other plant enzymatic activities) and non-biological (environmental factors, filling and storage practices).

2.5.3.1 Biological factors.

2.5.3.1.1 Plant respiration.

Maize silage kept in containers (silos) undergoes respiration to remove the oxygen trapped in the storage medium and create anaerobic conditions for fermentation (Muck, 1988).

The silo, when improperly sealed or slowly filled, allows oxygen entry which causes a loss of dry matter and ready fermentation of carbohydrates (McDonald, 1981) indicating a reduction in the value of energy. Studies have indicated that approximately 12% of dry matter is lost when removing oxygen from silos. Also, the onset of pH reduction is delayed due to microbial activity (Ruxton & McDonald, 1974) and heat produced which may increase the formation of acid-detergent insoluble N (Van Soest, 1982), especially when the silage temperature increases up to 60°C.

2.5.3.1.2 Aerobic microbial activity

Air which seeps into silos due to improper sealing encourages the growth of aerobic microbes (such as *Bacillus* spp. and yeasts) which can seriously damage the silage (Woolford, 1984). Mycotoxins may also be produced when certain moulds (such as *Aspergillus* and *Fusarium*) develop on silage (McDonald, 1984; Woolford, 1990). However, the aerobic stability of low crude protein silages (such as maize) is effectively improved when urea or ammonia is added at the ensiling phase (Britt, 1975).

2.5.3.1.3 Clostridial activity

Clostridia form the main anaerobic microbes which are very damaging to silage quality. They may either ferment carbohydrates and organic acids (saccharolytic clostridia) for the formation of CO_2, hydrogen and butyric acids or ferment amino acids (proteolytic clostridia) leading to the formation of ammonia, CO_2 and a variety of organic acids (McDonald, 1981). In ruminants, the production of butyric acid, ammonia and amines reduces *ad libitum* feed intake (Conrad *et al.,* 1977; Woolford, 1984).

2.5.3.1.4 Other Plant Enzymatic Activities

When maize forage is ensiled enzymes also remain active. For instance, hemicellulose and starch hydrolysis occurs with the formation of monosaccharides (or extra sugars) which are useful for lactic acid fermentation (Muck, 1988). Conversely, protein synthesising enzymes can convert protein N to peptides and free amino acids (non-protein N) whose further reduction into amines and ammonia are mainly caused by microbial activity (Ohshima & McDonald, 1978) thus reducing feeding value and increasing the cost of milk production. Proteolysis of maize silage in a silo or clamp is very high during the first day but declines after 5 days of fermentation (Bergen *et al.,* 1974).

2.5.3.1.5 The maturity stage at harvest

The maturity at harvest of the ensiling material plays a vital role in forage quality. It influences significantly the chemical composition of cell walls, the degree of its breakdown in rumen fluid (Cone & Engels, 1993) as well as plant protease (Muck, 1987). In a study on lucerne (*Medicago sativa*), the rate of proteolysis was found to be linearly and negatively correlated with the dry matter content of the forage (Muck ,1987) and thus, when the dry matter content is > 75% minimal proteolysis occurs. Schwarz *et al.* (1996) indicated that different maize silages with the same energy value may vary in animal performance due to differences in energy composition. The dry matter content of forage which is related to moisture activity (Greenhill, 1964) also influences the pH at which clostridial activity ceases (Wieringa, 1957). The effect of maturity on aerobic stability however does not follow a consistent pattern (Johnson *et al.,* 1999).

Harvesting at the right maturity stage also minimizes the activities of plant enzymes and undesirable epiphytic microorganisms (i.e. those naturally found in the plant) and encourages the activity of lactic acid bacteria (LAB) (McDonald, 1980). Bal *et al.* (1997) indicated that yield and protein production of milk was highest when cows were fed with maize harvested at ⅔ milkline stage (i.e. 35% dry matter) compared to those harvested at early dent (i.e. 30% dry matter). According to Hatew *et al.* (2016) emission of methane (CH_4) by dairy cows is reduced with increasing level of maturity of whole-plant maize silage. Digestion of crude protein, dry matter, acid-detergent fibre (ADF) and starch have also been found to be low when cows are fed with crops harvested at black layer stage (i.e. 40% dry matter) (Bal *et al.,* 1997). During grain filling, N uptake almost ceases whilst starch formation increases strongly with increasing percentage dry matter. Thus, the net effect is an increase in starch and energy content and a decline in protein as the proportion of grain increases through grain filling. The Table 2.2 below illustrates how maturity stage (in terms of dry matter content) of the ensiling material affects the quality of maize silage.

Table 2.2: Effect of maturity stage of ensiling material on the quality of maize silage.

	Dry matter content of maize silage (%)			
	42	35	32	31
Protein	7.0	7.1	7.3	7.5
Starch	37.4	37.2	28.7	18.2
Energy (MJME/kg DM)	10.5	10.6	10.1	9.2
ADF (%)	24.2	23.9	27.1	32.0
Milk yield (kg/day)	32.8	33.5	32.6	32.4
Dry matter intake (kg/DM)	25.4	25.8	25.7	25.6

Source: Bal *et al.* (1997)

2.5.3.2 Non-biological factors

2.5.3.2.1Climate

Environmental factors have been noted to negatively affect silage fermentation and aerobic stability (Muck, 1987; Garcia *et al.,* 1983). The occurrence of moisture (e.g. rain) during harvesting can reduce dry matter recovery by increasing the rate of protein breakdown in silos (McDonald *et al.,* 1991) and effluent production (Fransen & Strubi, 1998) due to the higher pH, ammonia-N concentration and lower lactic to acetic acid ratio (Adesogan & Kim, 2005). Moisture restores enzyme activity in dry forages and enhances the growth of proteolytic bacteria (Muck *et al.,* 2004)

When ensiled at high temperatures silage experiences a reduction in lactic acid concentration due to a reduction in the numbers of some lactic acid bacteria (Weinberg *et al.,* 2001), a reduction in aerobic stability and an increase in ammonia-N, pH, as well as dry matter losses (Ashbell *et al.,* 2002). However, inoculation with lactic acid bacteria resulted in good silage quality where sugar to crude protein ratio of the fresh material was < 0.4% and the sugar content > 6% on dry matter basis (Wieringa, 1960). Georing *et al.* (1973) also showed that the rate of occurrence of the Maillard reaction in silage increases exponentially with temperature, especially when silage is ensiled at temperatures ranging between 35°C and 40°C (Muck *et al.*, 2003). Maillard reaction (browning) is a chemical reaction (non-enzymatic) between amino acid and reducing sugar, which often requires heat (Martins *et al.,* 2001). Temperatures exceeding 45°C produced sweet brown silage and those below 40°C lead to the formation of sour silage with a repulsive smell (Amos & Williams, 1922).

2.5.3.2.2Filling and storage practices

The packing of silage plays a significant role in the movement of oxygen such that greater packing (density) reduces porosity and oxygen movement into silage in a clamp (Pitt, 1988). Slow filling of storage containers (silos) has been found to allow respiration and thus increase silage temperature which also increases proteolysis (McKersie, 1985; Muck, 1987; Wagner *et al.,* 2005).

CHAPTER THREE

Materials and methods

3.1 Experimental site

The study was conducted at the Horticultural Block (H 11) of the Faculty of Agriculture and Life Sciences. It is 12 m above sea level and located at latitude 43° 38' S and longitude 172° 28' E. The New Zealand Soil Bureau (1968) classified the soil as a Templeton silt loam which is intermediate between Lismore and Wakanui soils (Martin & Drewitt, 1982), with approximately 0.4-1.0 m silt loam and underlying gravel. According to Hewitt (1998) it was re-classified as Typic Immature Pallic Soil, a Recent soil developed on fine grey wacke alluvium with low phosphorus retention, moderate to high base saturation (> 50%) and low levels of extractable sulphate (Cox, 1978). This soil type, when using USDA Nomenclature is similar to "Udic Haplusept" (Soil-Survey-Staff, 1999). The mean monthly temperature, relative humidity (Appendix III) and precipitation (Appendix II) during the period of study (November, 2015 – April, 2016) were 9.25°C, 85% and 32.76 mm respectively (NIWA, 2016). The land prior to this study had perennial rye grass (*Lolium perenne*) growing on it and had not been sown with maize since 2006. The Lincoln weather station was situated about 2 kilometers away from the experimental plots.

3.2 Experimental design

The study area was 1,924 m^2 (74m * 26m) and a Randomised Complete Block Design (RCBD) was used (Appendix IV). The main plots of size 60m^2 (10m * 6m) focused on different row widths (i.e. 0.76m and 0.38m) whilst the sub-plots focused on different intra row

spacings (i.e. 0.12m, 0.18 and 0.24m) to obtain a range of plant densities (i.e. 54,824, 73,099, 109,649, 146,198, 219,298 plants/ha).

3.3 Experimental procedure(s)

3.3.1 Land preparation

The land for the experiment was sprayed with glyphosate (Roundup ultra ®) at an application rate of two litres/hectare in 200 litres of water on 27th July, 2015. It was then ploughed (30th Sept., 2015), rotary crumbled, Dutch harrowed and rolled (3rd – 4th Nov., 2015). The land was divided into four (4) blocks with each block having six (6) experimental plots measuring 10m * 6m ($60m^2$) each. An irrigator furrow of 6m was left between blocks to allow for easy passage of an irrigator.

3.3.2 Soil analysis

Soil samples were taken at 0-15cm and 16-30cm depths for laboratory analysis on the fertility status of the experimental plots. Soil tests on the 16th November, 2016 showed a pH of 5.7, an Olsen P level of 17mg/L, available N of 81 kg ha^{-1} and mineral N content of 49 kg ha^{-1} (Appendix II). Similarly, soil tests from adjacent plots meant for kale trials also indicated that basal fertilizer was not necessary even though the previous crop on this plot was grass.

3.3.3 Sowing

Pioneer Maize Hybrid P7524® seeds treated with Poncho® (an insecticide with Clothianidin as active ingredient), were drilled with a Stanhay precision drill at a depth of 3-5 cm on the 17th November, 2015 and plants later thinned to one seedling per hole after

emergence. Thus, ensuring that the intra-row spacing and population densities were attained. The 0.76m and 0.38 m row widths had 8 and 10 plant rows respectively per plot. The insecticide coating the sown seeds also formed a protective coating on seeds against maize pests such as Greasy cutworm (*Agrotis ipsilon*), Black beetle (*Heteronychus arator*) and Argentine stem weevil (*Listronotus bonariensis*) in a single treatment (Altmann, 2003). Pioneer Maize Hybrid P7524® is tall, large statured, early maturing and has high dry matter yield. It produces high yields under marginal soil conditions.

3.3.4 Weed control

Weeds competing with the cultivated crops were sprayed with Nu-Trazine™ 900DF (a post emergence selective herbicide containing 90g/kg of atrazine) at 800 grams/ha in 200 litres of water/ha on the 12th December, 2015 (4 weeks after planting).

3.3.5 Irrigation

Once emerged, crops were given 20mm of water every other week (in the absence of rain) using overhead sprinklers until after silking. A total of 135mm irrigation and 196.6mm rainfall were received by the crops during the period of study (Appendix I).

3.3.6 Fertilizer application

Urea 46% N was applied on the 8th December, 2015 (3 weeks after crop emergence) at a rate of 100kg/ha to give 30-50 kg N/ha, a standard general rate for maize silage (Cox & Cherney, 2001).

3.3.7 Treatments

Two main treatments (row widths of 76cm and 38cm) and three sub-treatments (12cm, 18cm and 24cm intra row spacing) were used for the study and each treatment replicated four (4) times to give twenty-four (24) experimental plots.

3.3.8 Harvesting

Prior to harvesting, two plants per plot were taken, chopped into smaller units, stems splitted open (to ensure thorough drying of samples) and oven-dried at 60°C for 24 hours. The dried samples were further grounded, again oven-dried at 105°C for 3 hours and the percentage dry matter content (%DM) determined (Australian Fodder Industry Association Ltd., 2011) after which the actual harvesting was carried out. The matured plants were manually harvested with a pair of shears at a cutting height of 10-15cm when dry matter content was 30-35% (Adesogan & Newman, 2014). The cutting height was aimed at increasing silage yield (Barnhart, 2009; Kung *et al*., 2008 & Lauer, 1998). Five (5) contiguous plants per experimental plot were initially harvested from the middle rows for the various yield assessments, oven-dried at 60°C for 48 hours and processed for NIR analysis of their nutritive values at harvest. A further 1m * 1m ($1m^2$) per plot was harvested for various forage yield assessments, fermented and later processed for silage quality analysis after fermentation (Appendix V). Thus, the 0.38m and 0.76m row widths had 3 rows and 2 rows respectively within the $1m^2$ area.

3.3.9 Silage Preparation

The crops harvested within the 1m * 1m ($1m^2$) area were chopped to approximately 1-3cm lengths using a SPITFIRE® wood chipper and filled into PVC type silos as described by

Toruk & Koc (2009). According to Kononoff *et al.* (2003) reducing the particle size increases dry matter intake and decreases chewing time. The PVC silos had dimensions of 16cm diameter and 40cm height (i.e. approximately 8 litres). The silage samples were packed into the PVC type silo and compressed manually to release pockets of air in the forage (Moran, 2005), covered with a cap and sealed tightly with gaffer tape® (Appendix VIIa) to prevent air entry. The samples were left to ferment for 100 days.

3.3.10 Near-Infra-Red (NIR) spectroscopy

NIRS method of analysis measures rapidly the chemical composition of samples with little or no sample preparation. It is based on the fact that each of the major chemical components of a sample has near infrared absorption properties which can be used to differentiate on component from others (Norris, 1989). The PVC silos after the period of fermentation were opened and approximately 15cm top layer of silage taken off (Appendix VIIb). Silage samples of approximately 700g were taken from the middle of the silo (Appendix VIIc), oven dried at 60°C for 48 hours, grinded with The Yeoman Major® grinder and passed through a sieve to obtain mean particle size from 100-500µm (Appendix VIII). Approximately 5g each were placed in sample cap and exposed to an electro-magnetic scan over a spectral wavelength ranging between 1100 and 2500nm (near infrared) using the NIRSystem 6500 FOSS®. The reflected energy was measured by the instrument and carried information which identified chemical bonds (such as –NH, OH and CH) within the sample (Corson *et al*., 1999). The reflected energy was stored as the reciprocal logarithm (log 1/R) and spectral transformed to provide information about the chemical composition of samples (Shenk & Westerhaus, 1993).

Samples with values outside the Global and Neighbourhood Hs range were further subjected to wet chemistry analysis (Australian Fodder Industry Association Ltd., 2011) at Riddolls Analytical Laboratory® for the various nutritive components considered in this study. The H referred to Hat (matrix) used to calculate mahalanobis distance. In NIR analysis, Global H values are used to determine samples with features different from the mean of majority of samples used to build an NIR equation (i.e. distance from the population mean) and its maximum value is 3. Neighbourhood H values are also used to determine if the scanned sample has similar samples in the database (i.e. distance from the closest sample) and has its value as 0.6.

3.4 Data collection

Physiological parameters: The following data were collected every two (2) weeks beginning when the crops reached 8 weeks after planting;

Leaf Chlorophyll content: The chlorophyll content of the sampled leaves was measured using SPAD-502 Chlorophyll Meter, Konica Minolta Sensing Inc., Japan®. Five plants in the two middle rows of each plot (Appendix V) were tagged and on each plant the true eighth (8th) leaf was used for measurements. Each leaf was divided into three sections (i.e. stalk, middle and tip) and SPAD readings were taken from each section. Thus, three chlorophyll readings per leaf and fifteen SPAD readings per plot and then averaged. The chlorophyll concentration of leaves was estimated using the equation proposed by Markwell *et al.* (1995):

$$\text{Chlorophyll } (\mu\text{mol m}^{-2}) = 10^{(\text{SPAD}\hat{}0.265)} \qquad \text{Equation 3.1}$$

where; SPAD was the mean SPAD-502 meter readings per plot.

Studies have indicated that SPAD meter readings correlate well with leaf nitrogen concentration (Schepers *et al*., 1992; Wood *et al*., 1992).

Photosynthetically Active Radiation (PAR): The photosynthetically active radiation was measured using a SunScan Canopy Analysis System® at 12, 14 and 17 WAP. The BF5 Sunshine Sensor when fixed on its tripod was placed at the center of the experimental field to ensure a stronger radio link for effective communication between the SunScan Probe and the sunshine sensor. The probe was used to take eight (8) readings per experimental plot on radiation intercepted by leaf canopy above knee level and also from the same direction (i.e. North-South direction) between 11.00 and 15.00 hours. The amount of radiation intercepted was estimated using the equation developed by Gallagher and Biscoe (1978):

$$\tau = 1 - \beta \qquad \text{Equation 3.2}$$

where, τ = photosynthetically active radiation intercepted

β = fraction of photosynthetically active radiation transmitted.

Growth & Yield parameters:

Plant height (cm): Plant height was measured every other week i.e. from 8WAP to 14WAP. The height of five sampled plants (Appendix V) was taken from ground level to the tip of the uppermost leaf.

Stem girth (cm): Stem girth was also measured every two weeks (i.e. from 8WAP to 14WAP) at the middle of the second internode (from the ground) of five sampled plants.

Number of leaves/plant: The number of leaves per plant was taken every other week (at 8, 10 and 12 WAP) and leaf after the coleoptile was regarded as leaf one (1).

Dry matter (DM) yield: The five (5) harvested samples were chopped into smaller units and stems splitted open to ensure thorough drying of samples. Samples were dried at 60°C for 72 hours in a forced air oven, weighed and the DM yield calculated using the equation:

Dry matter yield (t/ha) = Mean Dry Weight/crop x Population Density/ha

Forage yield (t DM/ha): From each plot an area measuring 1m * 1m ($1m^2$) was harvested, chopped and weighed. The 0.76m and 0.38m row widths had two and three crop rows respectively. 700g sub-samples from each of the $1m^2$ area were then oven-dried at 60°C for 72 hours after which their dry matter were determined. Fresh forage yield (t DM/ha) was determined using the equation:

Forage yield (t DM/ha) = Yield of wet crop (kg/ha) x dry matter %

Grain & Stover yield: The available ears from the five (5) sampled plants/plot (Appendix V) were oven-dried at 60°C for 72 hours and kernels shelled manually. The mean grain weight per cob determined and grain yield was calculated using the equation:

Grain yield (t/ha) = Mean grain weight/cob (kg) x No. of plants/ha

Stover yield was also determined using the equation:

Stover yield (t/ha) = (Mean plant dry weight-Mean kernel weight/cob) x No. of plants/ha.

Green:Dry leaf ratio: The five sampled plants for grain and stover yields were divided into green and dry leaves (Appendix VI) and each weighed separately. The green:dry leaves ratio of the fresh samples were then determined.

Stem:Leaf ratio: Stems of samples were weighed (Appendix VI) and the ratio of stem to leaf determined.

Cob diameter: Ear diameter was measured at the middle of the cob with vernier caliper, using dried cobs from the five sampled plants meant for grain/stover yields.

Number of kernels/row: The number of kernels per row on the dehusked ear was counted and recorded.

Number of kernel row/ ear: The dehusked ear was dissected transversely and the kernel rows counted and recorded.

Silage compaction: The level of silage compaction was assessed using the amount (kg) of silage per silo.

Silage quality parameters:

Silage crude protein: The crude protein level of samples was determined by the Kjeldahl method (Australian Fodder Industry Association Ltd., 2011) and crude protein calculated using the equation:

Percentage Crude Protein (% CP) = % N X 6.25

But Percentage Nitrogen (% N) = $\frac{(VS - VB) \times N (H_2SO_4) \times 14.007 \times 100}{W \times 1000}$

Where: VS = Volume, in ml, of standard H_2SO_4 required to titrate sample

VB = Volume, in ml, of standard H_2SO_4 required to titrate blank

N (H_2SO_4) = Normality of the acid titrant

14.007 = equivalent weight of Nitrogen

W = sample weight in grams

Acid Detergent Fibre (ADF) & Neutral Detergent Fibre (NDF): FiberCap™ Analyzer was used to determine the acid detergent fibre (ADF) and neutral detergent fibre (NDF) levels of samples using the procedures described by the Australian Fodder Industry Association Ltd. (2011).

Digestibility: The digestibility of dry matter was estimated (*in vitro*) using the pepsin-cellulase enzymatic procedure (Australian Fodder Industry Association Ltd., 2011).

Metabolisable Energy (ME): The metabolisable energy was also estimated from the measure of *in vitro* dry matter digestibility using the equation;

$$ME\ (MJ/kgDM) = 0.157 \times DOMD\ \%$$

where; DOMD % (Digestible Organic Matter in the DM) = (0.887 x DMD %) + 5.60

DMD = Dry Matter Digestibility

3.5 Data analysis

Data collected were subjected to two-way ANOVA using Genstat 16 and treatment means separated using Fisher's Protected Least Significance Difference ($p<0.05$). Relationships between some variable were further assessed using regression and correlation.

CHAPTER FOUR

Results

Table 4.1: Leaf chlorophyll concentration of *Zea mays* as affected by row width and intra-row spacing at 8, 10, 12 and 14weeks after planting (WAP).

Treatment(s)	Leaf chlorophyll concentration (µmol m^{-2})			
	8WAP	**10WAP**	**12WAP**	**14WAP**
T_2 (0.76m * 0.24m)	565.5_a	586.5_a	924.2_{ab}	931.6_{ab}
T_1 (0.76m * 0.18m)	638.5_{ab}	661.0_{ab}	1038.1_b	1023.1_b
T_3 (0.76m * 0.12m)	665.5_{ab}	688.6_{abc}	1002.9_{ab}	970.4_{ab}
T_4 (0.38m * 0.24m)	742.6_b	862.3_d	992.8_{ab}	972.5_{ab}
T_5 (0.38m * 0.18m)	607.5_a	731.2_{bcd}	868.4_a	869.8_a
T_6 (0.38m * 0.12m)	678.1_{ab}	806.5_{cd}	948.2_{ab}	965.9_{ab}
P-value (5%)	<0.003	< 0.001	<0.015	<0.006
SE	49.64	53.74	60.73	45.34
CV%	7.3	7.4	6.3	4.7

Means with the same letter subscript are not significantly different at α=0.05

There were significant differences (P<0.003) in leaf chlorophyll concentration at 8 WAP, which were partly due to row width effect (P<0.02) and the interaction between row width and intra row spacing (P<0.002). The values recorded ranged from 565.5µmol m^{-2} to 742.6µmol m^{-2}.

The row width and its interaction with plant spacing was evident in the values recorded by T_3 (665.5 µmol m^{-2}) and T_4 (742.6µmol m^{-2}) which were at the same population density.

At 10 WAP, treatment means were significantly different ($P<0.001$). The observed difference were as a result of row width ($P<0.001$) and its interaction with plant spacing ($P<0.004$) effect which was still clear between T_3 (688.6µmol m^{-2}) and T_4 (862.3µmol m^{-2}).

At 12 WAP there were also significant differences ($P<0.015$) between means. However, the row width effect was insignificant ($P<0.054$) compared to the previous weeks but the interaction between row width and plant spacing remained significant ($P<0.005$). Generally, the 0.76m row width showed a 53.15% increase in mean chlorophyll concentration at 12 WAP, compared to the values at 10 WAP. Similarly, the 0.38m row width also recorded a 17.06% increase compared with 10 WAP. However, mean increase in chlorophyll concentrations for 0.76m and 0.38m row widths from 8 WAP to 10 WAP were 3.56% and 18.33% respectively, indicating great increase for 0.76m row width.

The increasing trend in leaf chlorophyll concentration observed in the previous weeks (i.e. from 8WAP to 12 WAP) began to change at14 WAP. Then, chlorophyll concentrations declined, in that the 0.76m and 0.38m row widths recorded 1.35% and 0.04% reduction respectively, compared to the previous weeks increases. Treatment means were significantly different ($P<0.006$), which was mainly due to row width and intra row spacing interaction ($P<0.002$). The recorded values ranged from 869.8µmol m^{-2} to 1023.1µmol m^{-2}.

Table 4.2: Row width and intra-row spacing effect on radiation interception of *Zea mays* at 12, 14 and 17 weeks after planting (WAP).

Treatment(s)	Radiation interception		
	12WAP	**14WAP**	**17WAP**
T_2 (0.76m * 0.24m)	0.903_{bc}	0.870_{b}	0.880_{b}
T_1 (0.76m * 0.18m)	0.793_{a}	0.756_{a}	0.775_{a}
T_3 (0.76m * 0.12m)	0.885_{b}	0.856_{b}	0.895_{bc}
T_4 (0.38m * 0.24m)	0.916_{bc}	0.895_{bc}	0.895_{bc}
T_5 (0.38m * 0.18m)	0.938_{bc}	0.925_{bc}	0.945_{cd}
T_6 (0.38m * 0.12m)	0.960_{c}	0.973_{c}	0.963_{d}
P-value (5%)	<0.001	<0.001	<0.001
SE	0.0293	0.0331	0.0262
CV%	3.3	3.8	2.9

Means with the same letter subscript are not significantly different at α=0.05

The intercepted photosynthetically active radiation (iPAR) recorded at 12 WAP indicated significant difference (P<0.001) between treatment means, partly due to row width (P<0.001), intra row spacing (P<0.003) and their interaction (P<0.002). The mean iPAR was 0.899 and values ranged from 0.793 to 0.960

The mean iPAR decreased by 2.11% (i.e. from 0.899 to 0.880) though there were significant differences ($P<0.001$) between treatment means at 14 WAP. Row width, intra row spacing ($P<0.002$) and their interaction accounted for these observed differences.

At 17 WAP, mean iPAR increased again by 1.36% (i.e. from 0.880 to 0.892) with values ranging from 0.775 to 0.963. Significant differences ($P<0.001$) were observed between treatment means. Row width ($P<0.001$), intra row spacing ($P<0.001$) and their interaction ($P<0.001$) contributed significantly to these observed differences. Generally, T_6 (0.38m * 0.12m) with the highest plant population (219,298 plants/ha) recorded the highest values throughout the period of measurement. However, T_2 (0.76m * 0.24m) with the lowest population (54,824 plants/ha) recorded values which were higher than those of T_1 (0.76m * 0.18m) which had 73,099 plants/ha.

Table 4.3: Effect of row width and intra-row spacing on plant height of *Zea mays* at 8, 10, 12 and 14 weeks after planting (WAP).

Treatment(s)	Plant Height (cm)			
	8WAP	**10WAP**	**12WAP**	**14WAP**
T_2 (0.76m * 0.24m)	101.0_a	134.6_a	216.5_a	246.6_a
T_1 (0.76m * 0.18m)	108.0_a	141.6_a	226.3_a	243.8_a
T_3 (0.76m * 0.12m)	99.9_a	133.5_a	224.1_a	249.5_a
T_4 (0.38m * 0.24m)	111.8_a	145.4_a	227.1_a	249.2_a
T_5 (0.38m * 0.18m)	104.1_a	137.7_a	218.9_a	244.4_a
T_6 (0.38m * 0.12m)	105.7_a	139.3_a	221.6_a	252.8_a
P-value (5%)	<0.184	< 0.184	<0.206	<0.398
SE	6.72	6.72	6.53	6.53
CV%	6.4	4.8	2.9	2.6

Means with the same letter subscript are not significantly different at α=0.05

There were no significant differences (P<0.184) between treatment means at 8 WAP and 10 WAP when plant height ranged from 99.9cm to111.8cm at 8 WAP and from 133.5cm to 145.4cm at 10 WAP.

Similarly, there were no significant differences between treatment means at 12 WAP ($P<0.206$) and 14 WAP ($P<0.398$) indicating that neither row width, intra row spacing nor their interaction influenced plant height.

Table 4.4: Stem girth of *Zea mays* as influenced by row width and intra-row spacing at 8, 10 and 12 weeks after planting.

Treatment(s)	Stem girth (cm)		
	8WAP	**10WAP**	**12WAP**
T_2 (0.76m * 0.24m)	6.67_{ab}	7.22_{ab}	8.20_{a}
T_1 (0.76m * 0.18m)	7.10_{b}	8.08_{b}	8.98_{a}
T_3 (0.76m * 0.12m)	6.68_{ab}	7.49_{ab}	8.80_{a}
T_4 (0.38m * 0.24m)	6.86_{ab}	7.92_{b}	8.60_{a}
T_5 (0.38m * 0.18m)	6.25_{a}	7.96_{a}	7.97_{a}
T_6 (0.38m * 0.12m)	6.61_{ab}	7.48_{ab}	8.49_{a}
P-value (5%)	<0.025	<0.008	<0.189
SE	0.296	0.379	0.615
CV%	3.3	5.0	7.2

Means with the same letter subscript are not significantly different at $\alpha=0.05$

At 8 WAP there were significant differences ($P<0.025$) in plant stem girth. Mean stem girth was 6.69 cm with values ranging from 6.25cm to 7.10cm. The observed differences were affected the the row width-intra row spacing interaction ($P<0.009$).

At 10 WAP, mean stem girth increased by 12.56% (i.e. from 6.69cm to 7.53cm). These significant differences ($P<0.008$) were due to row width-intra row spacing interactions ($P<0.001$) rather than row width ($P<0.378$) or intra row spacing ($P<0.899$).

Mean stem girth again increased by 13.41% at 12 WAP (from 7.53cm to 8.54cm) but there was no significant difference ($P<0.189$) between treatments. The results indicated that T_6 (0.38m * 0.12m) with the highest population density (219,298 plants/ha), had higher stem girth throughout the period of measurement compared with T_5 (0.38m * 0.18m) with 146,198 plants/ha. Conversely, T_2 (0.76m * 0.24m) with the lowest plant population density (54,824 plants/ha) recorded lower stem girth values compared with T_1 (0.76m * 0.18m) with 73.099 plants/ha.

Table 4.5: Number of leaves/plant of *Zea mays* as influenced by row width and intra-row spacing at 8, 10 and 12 weeks after planting (WAP).

Treatment(s)	Number of leaves/plant		
	8WAP	**10WAP**	**12WAP**
T_2 (0.76m * 0.24m)	7.27_a	9.22_a	12.95_a
T_1 (0.76m * 0.18m)	7.64_a	9.59_a	12.75_a
T_3 (0.76m * 0.12m)	7.67_a	9.62_a	12.96_a
T_4 (0.38m * 0.24m)	7.61_a	9.56_a	13.00_a
T_5 (0.38m * 0.18m)	7.25_a	9.20_a	12.63_a
T_6 (0.38m * 0.12m)	7.06_a	9.01_a	12.92_a
P-value (5%)	<0.041	<0.041	<0.652
SE	0.291	0.291	0.350
CV%	3.9	3.1	2.7

Means with the same letter subscript are not significantly different at α=0.05

Number of leaves per plant at 8WAP and 10 WAP recorded some differences (P<0.041) between treatment means which were mainly due to row width and intra row spacing interactions (P<0.013) rather than row width (P<0.087) and intra row spacing (P<0.829). Leaf numbers ranged from 7.06 to 7.61 at 8WAP and 9.01to 9.62 at 10 WAP.

However, no significant difference was observed ($P<0.625$) between means at 12 WAP. Mean number of leaves per plant was 12.86, a 37.25% increase from previous fortnight's measurement.

Table 4.6: Effect of row width and intra-row spacing on Green:Dry leaves and Leaves:Stem of *Zea mays.*

Treatment(s)	Green leaves:Dry leaves(g/g)	Leaves:Stem(g/g)
T_2 (0.76m * 0.24m)	9.8_a	0.604_a
T_1 (0.76m * 0.18m)	18.1_a	0.587_a
T_3 (0.76m * 0.12m)	10.6_a	0.550_a
T_4 (0.38m * 0.24m)	11.5_a	0.574_a
T_5 (0.38m * 0.18m)	10.1_a	0.645_a
T_6 (0.38m * 0.12m)	13.5_a	0.610_a
P-value (5%)	< 0.502	<0.252
SE	6.63	0.055
CV%	54.0	9.2

Means with the same letter subscript are not significantly different at α=0.05

Treatment means recorded no significant difference (P<0.502) in terms of green leaves-dry leaves ratio at P<0.05. Values ranged from 9.8 to 18.1 with the mean being 12.29.

The treatment means for leaves-stem ratio were also not significantly different (P<0.252) at α = 0.05. The mean leaves-stem ratio recorded was 0.595 and values ranged from 0.550 to 0.645.

Table 4.7: Row width and intra-row spacing effect on cob diameter, cob length, cob weight, number of kernels/row and kernel rows/ear of *Zea mays* at physiological maturity (1470° C.d).

Treatment(s)	Cob diameter (mm)	Cob length (mm)	Cob weight (g)	Number of kernels/row	Kernel rows/ear
T_2 (0.76m * 0.24m)	41.76_a	170.7_b	291.5_{ab}	30.65_a	12.45_{ab}
T_1 (0.76m * 0.18m)	43.98_b	172.0_b	356.6_c	29.70_a	13.10_b
T_3 (0.76m * 0.12m)	42.44_a	165.8_{ab}	307.5_b	28.98_a	12.85_{ab}
T_4 (0.38m * 0.24m)	43.11_{ab}	169.0_b	314.1_b	29.74_a	13.05_{ab}
T_5 (0.38m * 0.18m)	42.70_{ab}	160.7_a	289.9_{ab}	29.30_a	12.80_{ab}
T_6 (0.38m * 0.12m)	42.00_a	164.8_{ab}	277.8_a	29.93_a	12.35_a
P-value (5%)	< 0.045	<0.058	<0.001	<0.571	<0.215
LSD	1.40	7.64	29.08	1.94	0.729
SE	0.930	2.53	9.65	0.64	0.245
CV%	2.2	3.03	6.30	3.8	3.79

Means with the same letter subscript are not significantly different at α=0.05

There were no significant differences ($P<0.045$) between treatments for cob diameter which ranged from 41.76mm to 43.93mm with the mean being 42.67mm. Mean cob diameter for the 0.38m row width was 0.16mm greater than that of the 0.76m row width.

Cob length also showed no significant differences ($P<0.058$) between treatments. The recorded values ranged from 160.7mm to 172.0mm with the average being 167.2mm. The 0.76m row width showed a slight increase in mean cob length (i.e. 4.67mm) compared to the 0.38m row width though insignificant at $\alpha = 0.05$.

There were significant differences ($P<0.001$) in cob weight between treatments, a result of row width ($P<0.007$) and intra row spacing ($P<0.019$) effects as well as their interaction ($P<0.001$). The values ranged from 277.8g to 356.6g. Treatments, T_1 (0.76m * 0.18m) and T_6 (0.38m * 0.12m) recorded the highest and lowest cob weights respectively. Also, treatments which were at the same plant population i.e. T_3 (0.76m * 0.12m) and T_4 (0.38m * 0.24m) recorded values (307.5g and 314.1g respectively) which were not much different from each other, illustrating the slight impact of the factors (i.e. row width and intra row spacing) and their interaction. Interestingly, treatments with the lowest (T_2) and highest (T_6) plant populations recorded no significant.

Row width and intra-row spacing effects on number of kernels per row were insignificant ($P<0.571$) at $\alpha = 0.05$. The recorded values ranged between 28.98 and 30.65.

Similarly, there were no significant differences ($P<0.215$) in term of kernel rows per ear between treatments. Mean kernel rows/ear was 12.77 and values ranged from 12.35 to 13.10.

Table 4.8: Row width and intra-row spacing effect on grain yield, dry matter yield, forage yield and stover yield of *Zea mays* .

Treatment(s)	Grain yield (t ha^{-1})	Dry matter yield (t ha^{-1})	Forage yield (t DM ha^{-1})	Stover yield (t ha^{-1})
T_2 (0.76m * 0.24m)	7.15_a	7.86_a	32.55_a	6.43_a
T_1 (0.76m * 0.18m)	11.37_b	13.47_b	31.40_a	11.20_b
T_3 (0.76m * 0.12m)	15.62_c	17.98_c	35.32_a	14.86_c
T_4 (0.38m * 0.24m)	16.27_c	18.18_c	29.30_a	14.93_c
T_5 (0.38m * 0.18m)	20.31_d	20.20_c	29.34_a	16.14_d
T_6 (0.38m * 0.12m)	30.00_e	30.53_d	31.14_a	24.52_e
P-value (5%)	< 0.001	<0.001	<0.559	<0.001
LSD	1.82	2.59	7.53	1.74
SE	0.61	0.89	2.49	0.579
CV%	7.2	9.52	15.9	9.87

Means with same letter subscript are not significantly different at α=0.05

The results (Table 4.8) showed an increase in grain yield (t ha^{-1}) from 7.15 t ha^{-1} to 30 t ha^{-1} with the mean grain yield being 16.79 t ha^{-1}. There were significant differences between treatments ($P<0.001$). Row width and intra row spacing interactions contributed greatly ($P<0.001$) to the observed differences. Grain yield increased with increasing plant population density. At constant intra row spacing, the 0.38m row width increased of between 78.6% and 127.6% over 0.76m row width.

Dry matter (DM) yield was significantly different ($P<0.001$) between treatments. The mean DM yield was 18.04t ha^{-1} with values ranging from 7.86 t ha^{-1} to 30.53t ha^{-1}. DM yield generally increased with increasing plant population. Mean DM yield for the 0.76m and 0.38m row widths were 13.10 t ha^{-1} and 22.97 t ha^{-1} respectively.

Forage yield (t DM ha^{-1}) did not show any significant difference ($P<0.559$) between treatments. Mean forage yield ranged from 29.30 t DM ha^{-1} to 35.32 t DM ha^{-1}.

There were significant differences in stover yield ($P<0.001$) between treatments. The yield increased from 6.43 t ha^{-1} to 24.52 t ha^{-1} with the mean stover yield being 14.68 t ha^{-1}. Increasing plant population resulted in increasing stover yield. Row width and intra row spacing interaction contributed to the observed differences. The percentage increase in stover yield ranged from 44.1 to 132.2%. Mean stover yield for 0.38m row width was 7.7 t ha^{-1} greater than the 0.76m row width.

Table 4.9: Quantity of silage (kg)/silo (Level of silage compaction)

Treatment(s)	Level of silage compaction (kg)
T_2 (0.76m * 0.24m)	2.28_a
T_1 (0.76m * 0.18m)	2.47_a
T_3 (0.76m * 0.12m)	2.29_a
T_4 (0.38m * 0.24m)	2.33_a
T_5 (0.38m * 0.18m)	2.03_a
T_6 (0.38m * 0.12m)	2.03_a
P-value (5%)	< 0.067
SE	0.108
CV%	9.61

Means with the same letter subscript are not significantly different at α=0.05

The level of silage compaction was measured using the amount/quantity of silage per silo (with the same volume). There was no significant difference (P<0.067) in the level of silage compaction between treatments. The amount (kg) of silage per silo ranged from 2.03 kg to 2.47 kg with the mean being 2.24 kg. Thus, the amount of chopped maize/silo prior to ensiling did not differ between treatments. Therefore, differences in nutritive value of silage (if any) cannot be attributed to packing or the level of compaction.

Table 4.10: Row width and intra-row spacing effect on acid detergent fibre (ADF), neutral detergent fibre (NDF), crude protein (CP), metabolizable energy (ME) and dry matter digestibility (DMD) of *Zea mays* at harvest and silage.

Treatment(s)	At Harvest					After Fermentation (Silage)				
	ADF (%)	**NDF (%)**	**CP (%)**	**ME**	**DMD**	**ADF (%)**	**NDF (%)**	**CP (%)**	**ME**	**DMD**
T_2 (0.76m * 0.24m)	21.21_{ab}	45.98_{ab}	5.68_{a}	10.30_{ab}	70.55_{a}	19.07_{a}	34.83_{a}	8.03_{ab}	11.50_{a}	71.53_{a}
T_1 (0.76m * 0.18m)	22.43_{b}	49.61_{b}	6.39_{b}	9.80_{a}	70.70_{a}	18.76_{a}	35.01_{a}	8.53_{b}	11.60_{a}	71.78_{a}
T_3 (0.76m * 0.12m)	21.91_{b}	48.11_{b}	6.15_{ab}	9.99_{ab}	70.72_{a}	18.79_{a}	36.36_{a}	8.23_{b}	11.35_{a}	71.14_{a}
T_4 (0.38m * 0.24m)	21.87_{b}	47.14_{b}	5.86_{ab}	10.10_{ab}	69.73_{a}	17.32_{a}	32.60_{a}	7.98_{ab}	12.03_{a}	74.26_{a}
T_5 (0.38m * 0.18m)	20.56_{ab}	45.17_{ab}	6.19_{ab}	10.28_{ab}	71.87_{a}	16.80_{a}	33.66_{a}	7.13_{a}	11.68_{a}	73.22_{a}
T_6 (0.38m * 0.12m)	17.54_{a}	40.23_{a}	6.15_{a}	10.83_{b}	73.08_{a}	18.86_{a}	36.60_{a}	7.14_{a}	11.44_{a}	71.34_{a}
P-value (5%)	< 0.144	<0.096	<0.137	<0.321	<0.410	<0.806	<0.791	<0.063	<0.845	<0.833
LSD	3.83	6.44	0.55	0.95	3.43	4.30	6.76	1.07	1.16	5.85
SE	1.27	2.14	0.18	0.31	1.14	1.43	2.24	0.35	0.38	1.94
CV%	12.1	9.28	6.0	6.14	3.2	15.6	12.9	9.02	6.61	5.38

There were no significant differences in Acid Detergent Fibre (P<0.144) between treatments at harvest. ADF values at harvest ranged from 17.54% to 22.43%. Similarly, ADF for silage (after fermentation) also showed no significant difference (P<0.806). Mean silage ADF was smaller (18.27%) than that at harvest (20.92%).

The Neutral Detergent Fibre (NDF) values were not significantly different between treatments both at harvest (P<0.096) and after fermentation (P<0.791). The NDF values at harvest ranged from 40.23% to 49.61% whilst that of the silage was from 32.60% to36.60%. The mean NDF at harvest and for the silage were 46.06% and 34.84% respectively, indicating 24.33% reduction in mean NDF after fermentation.

Crude protein levels were not significantly different between treatments both at harvest (P<0.140) and after fermentation (<0.063). Crude protein at harvest ranged from 5.86% to 6.39% whilst that of the silage was from 7.13% to 8.53%. Mean crude protein level of silage was 29.16% higher than at harvest.

Metabolizable energy values at harvest ranged from 9.80 MJ/kg DM to 10.83 MJ/kg DM and there were no significant differences (P<0.325) between treatments. Similarly, ME values for the silage showed no significant difference (P<0.842). The mean silage ME was 11.60 MJ/kg DM with values ranging from 11.50 MJ/kg DM to 12.03 MJ/kg DM. Treatment, T_4 (0.38m * 24m) also showed slight increase in ME over T_3 (0.76m * 0.12) both at harvest (0.11 MJ/kg DM) and after fermentation (0.68 MJ/kg DM) even though both treatments were at the same plant population (109,649 plants/ha). Again, the highest and lowest ME values both at harvest and that of silage were associated with 0.38m and 0.76m row widths respectively.

Dry matter digestibility (DMD) did not record significant difference both at harvest ($P<0.410$) and after fermentation ($P<0.833$). DMD values ranged between 69.73 – 73.08% at harvest and 71.14 – 74.26% for the silage. The 0.38m row width recorded highest DMD values both at harvest (73.08%) and after fermentation (74.26%).

CHAPTER FIVE

Discussion

5.1 Growth parameters as affected by row width and intra row spacing

5.1.1 Plant Height (cm)

There were no significant differences in plant height between treatments throughout the period of measurement (Table 4.3). The 0.38m row width recorded the highest plant height values which was probably due to the effect of etiolation (shading). This finding was contrary to the outcome of a study conducted by Abuzar *et al*. (2011) where the highest plant population density produced short statured crops due to increased competition between plants for resources such as nutrients, light and water. However, the information (Table 4.3) supported the studies conducted by Sharifi *et al*. (2009) and Lashkari *et al*. (2011) where the highest plant height values were associated with maximum plant population density. According to Lashkari *et al*. (2011) this is because there is increased plasticity under which the Far-red/Red ratio of intercepted radiation increases with increasing population density triggering physiological events and leading to prioritization and allocation of assimilates to the main stem to increase plant height.

5.1.2 Stem Girth (cm)

Generally, stem girth decreased with increasing PAR interception (Figs. 5.1, 5.2 & 5.3). These observations are similar to the results of a study conducted by Baghdadi *et al.* (2012), when maize stem diameter decreased with increasing plant population. This presupposes that the increasing plant population increased the stress level of plants through competition for resources, which negatively affected stem girth. Makinde *et al*. (2009) observed a similar trend with jute

(*Corchorus olitorus* L.) when stem girth decreased gradually with increasing population density mainly due to intra population competition. Similar observations were recorded in other studies with *Hibiscus cannabinus* (Higgins & White, 1970) and *Atriplex prostrata* (Wang *et al*., 2005).

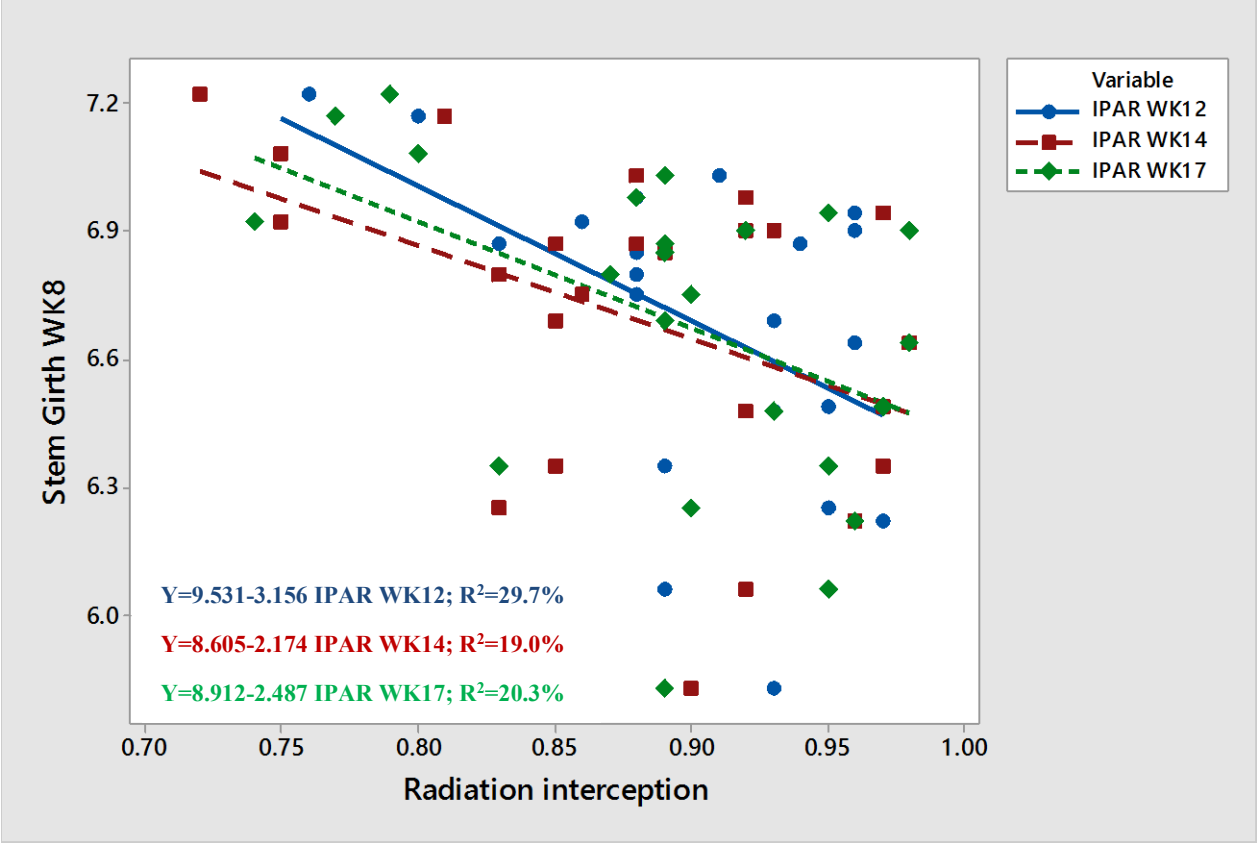

Fig. 5.1: Stem girth of *Zea mays* at 8 WAP as influenced by radiation interception.

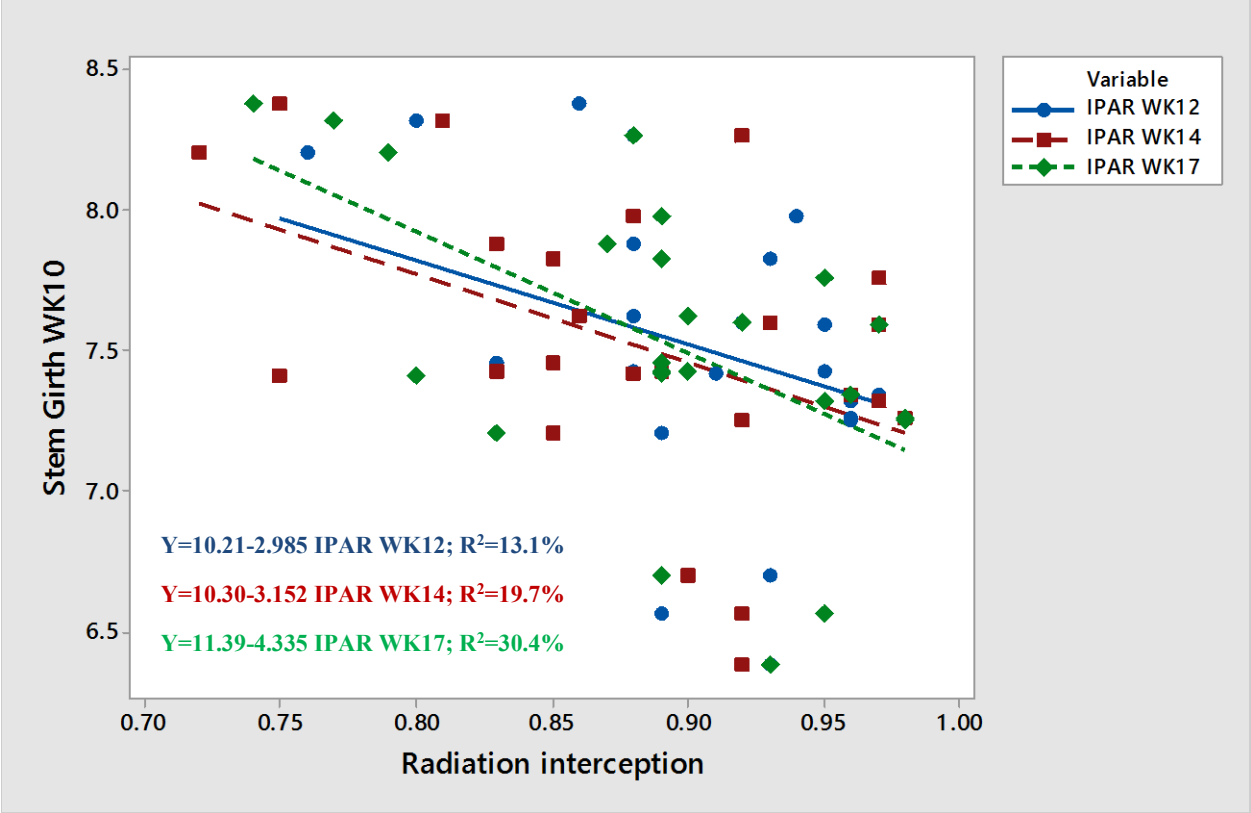

Fig. 5.2: Stem girth of *Zea mays* at 10 WAP as influenced by radiation interception.

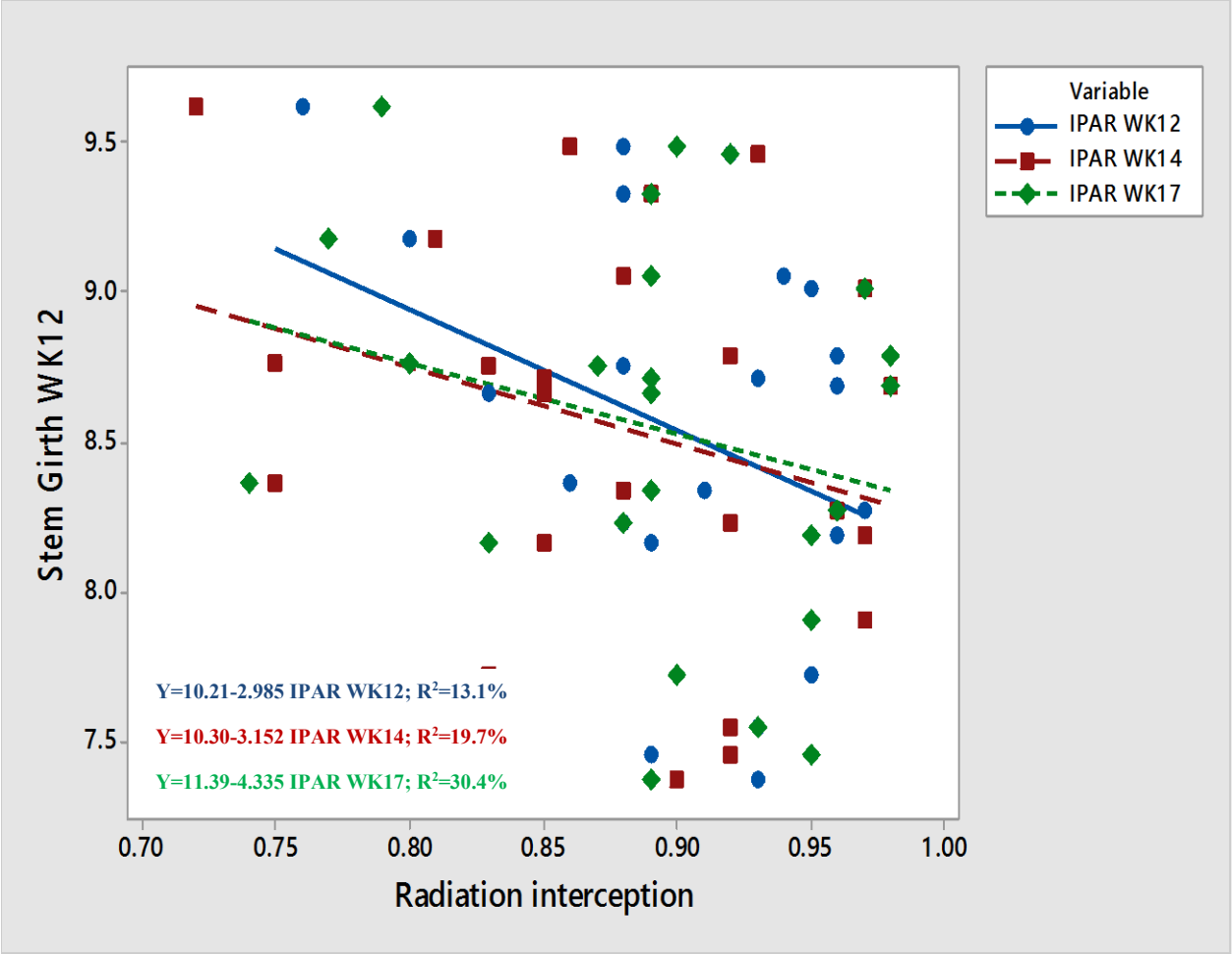

Fig. 5.3: Stem girth of *Zea mays* at 12 WAP as influenced by radiation interception

5.1.3 Number of leaves/plant

The mean number of leaves/plant at 10 WAP (9.37) and 12 WAP (12.86) increased by 26.28% and 37.25% respectively from their previous fortnight's data but no differences were significant (Table 4.5). This finding is in line with a study conducted by Sangoi and Salvador (1998) which indicated that number of leaves /plant is significantly affected by genotype and not by plant population density.

5.1.4 Leaves/Stem ratio

Row width and intra row spacing had no significant impact (P<0.252) on leaves/stem ratio. This is contrary to a study by Baghdadi *et al*. (2012b) where plant population density significantly affected leaves/stem ratio of maize. NeSmith (1998) in a similar study with collards (*Brassica oleracea* L. Acephala Group) showed that leaves/stem ratio decline linearly with plant population density exceeding 5 plants/m^2.

5.1.5 Green leaves/Dry leaves ratio

There were no significant differences (P<0.502) between treatments in terms of Green leaves/Dry leaves ratio (Table 4.6). Thus, neither row width, intra row spacing nor their interaction (plant population density) could influence green leaves/dry leaves ratio. In a study by Borrás *et al*. (2003), plant population density only affected rate of senescence but could not influence the ontogenic stage when senescence was initiated. This presupposes that the maize variety might possess "stay green" trait. Leaf senescence is a programmed cell death and controlled genetically (Hopkins & Huner, 2004).

5.2 Yield parameters as influenced by row width and intra row spacing

5.2.1 Cob Diameter (mm)

There were no significant differences in cob diameter between treatments at $\alpha = 0.05$ (Table 4.7). In spite of the significant differences recorded in terms of radiation interception by the various treatments (Table 4.2), it had minimal effect on cob diameter. Cob diameter generally increased with decreasing radiation interception (Fig. 5.4). Plants with narrow row widths which

intercepted the highest PAR recorded the low cob diameter values. This suggests that the higher plant population increased stress and competition for resources (Adeniyan, 2014). Duncan (1984) also suggested that a plant population above a critical density adversely affects yield per plant due to interplant competition for resources such as nutrients, water and other yield limiting factors. However, comparison of the regression lines for IPAR and cob diameter indicated no significant difference (i.e. P=0.268, P=0.319 and P=0.221 for IPARs 12, 14 and 17 respectively).

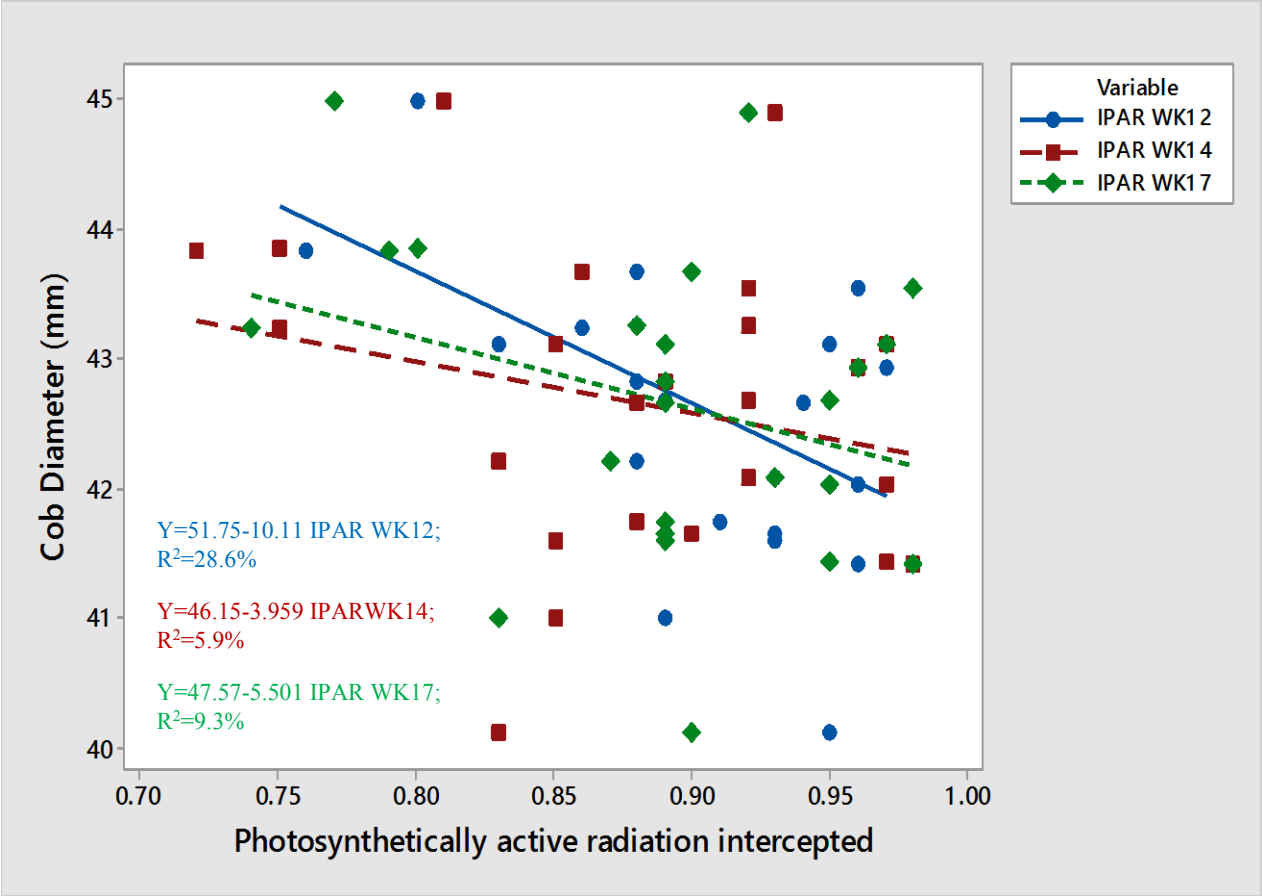

Fig. 5.4: Cob diameter (mm) of *Zea mays* versus radiation interception at 12, 14 and 17 weeks after planting (WAP).

Although cob diameter increased linearly with increasing leaf chlorophyll concentration (Fig. 5.5) the correlation between these variables was very weak (i.e. r = 0.24, r = 0.14, r = 0.47

and r = 0.37 at 8WAP, 10WAP, 12WAP and 14WAP respectively). Onasanya *et al*. (2009) found cob diameter to increase with increasing nitrogen and phosphorus application. Similarly, Gul *et al*. (2015) recorded significant differences (P<0.05) in cob diameter and indicated that it increased with increasing nitrogen, phosphorus and potassium levels. Again, the fitted lines were not different significantly from each other (i.e. P=0.291, P=0.653, P=0.420 for leaf chlorophyll concentrations 14, 12 and 10 respectively).

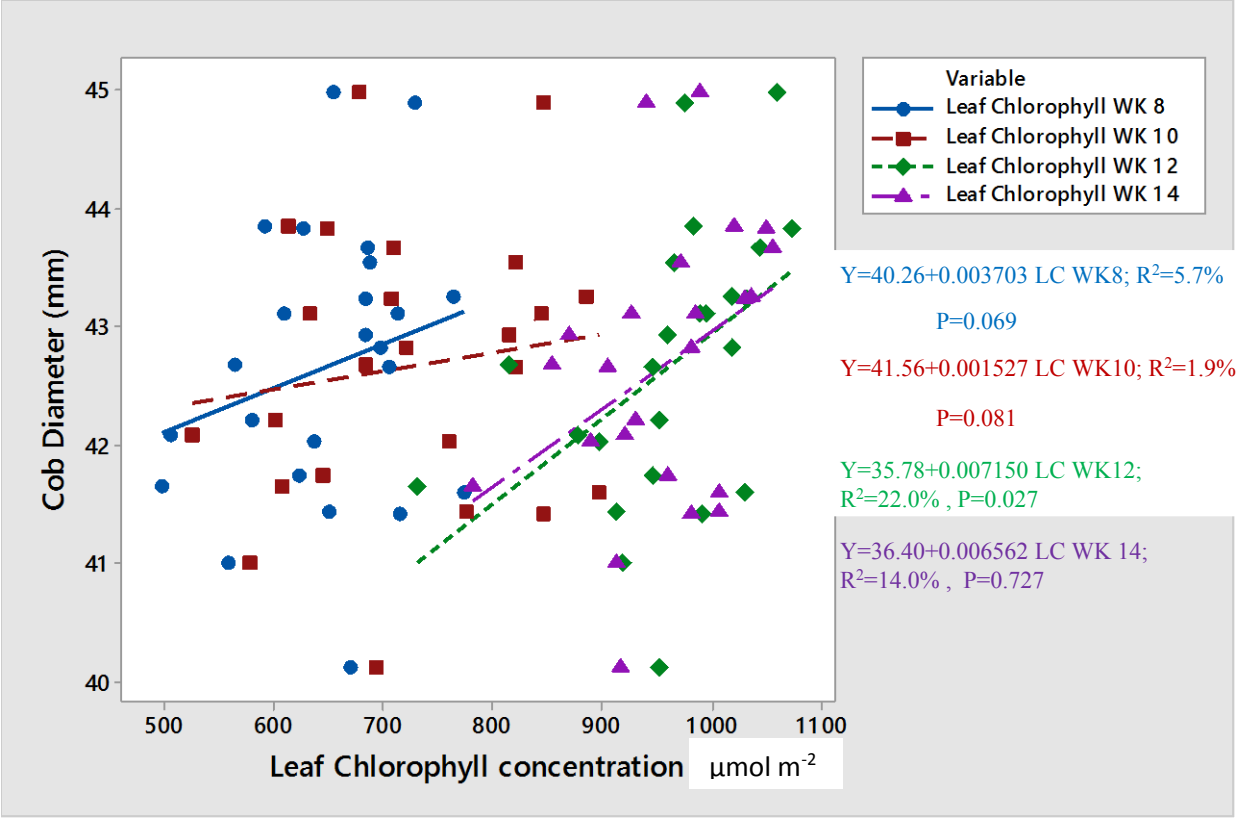

Fig. 5.5: Cob diameter of *Zea mays* as influenced by leaf chlorophyll concentration.

5.2.2 Cob weight (g)

Cob weight generally increased linearly with leaf chlorophyll concentration (Fig. 5.6) although at 10 WAP it was found to be inversely related with leaf chlorophyll concentration. The

relationship between cob weight and leaf chlorophyll concentration was also found to be very weak (r = 0.16) at 8 WAP. However, an increased (stronger) relationship was observed at 12 WAP (r = 0.56) and 14 WAP (r = 0.46). Several studies associate maize yield response to high levels of nitrogen in the soil (Sinclair & Muchow, 1994). The specific leaf nitrogen (minimum amount of leaf N per unit leaf area required for expansion) for maize has been found to be higher compared to sorghum (Muchow, 1988a). However, there has been little research into exact relationship between cob weight and leaf chlorophyll concentration. The comparison of regression fitted lines for cob weight and leaf chlorophyll concentration also revealed no significant difference (i.e. P=0.15, P=0.28 and 0.12 for cob weight at leaf chlorophyll concentrations 14, 12 and 10 respectively).

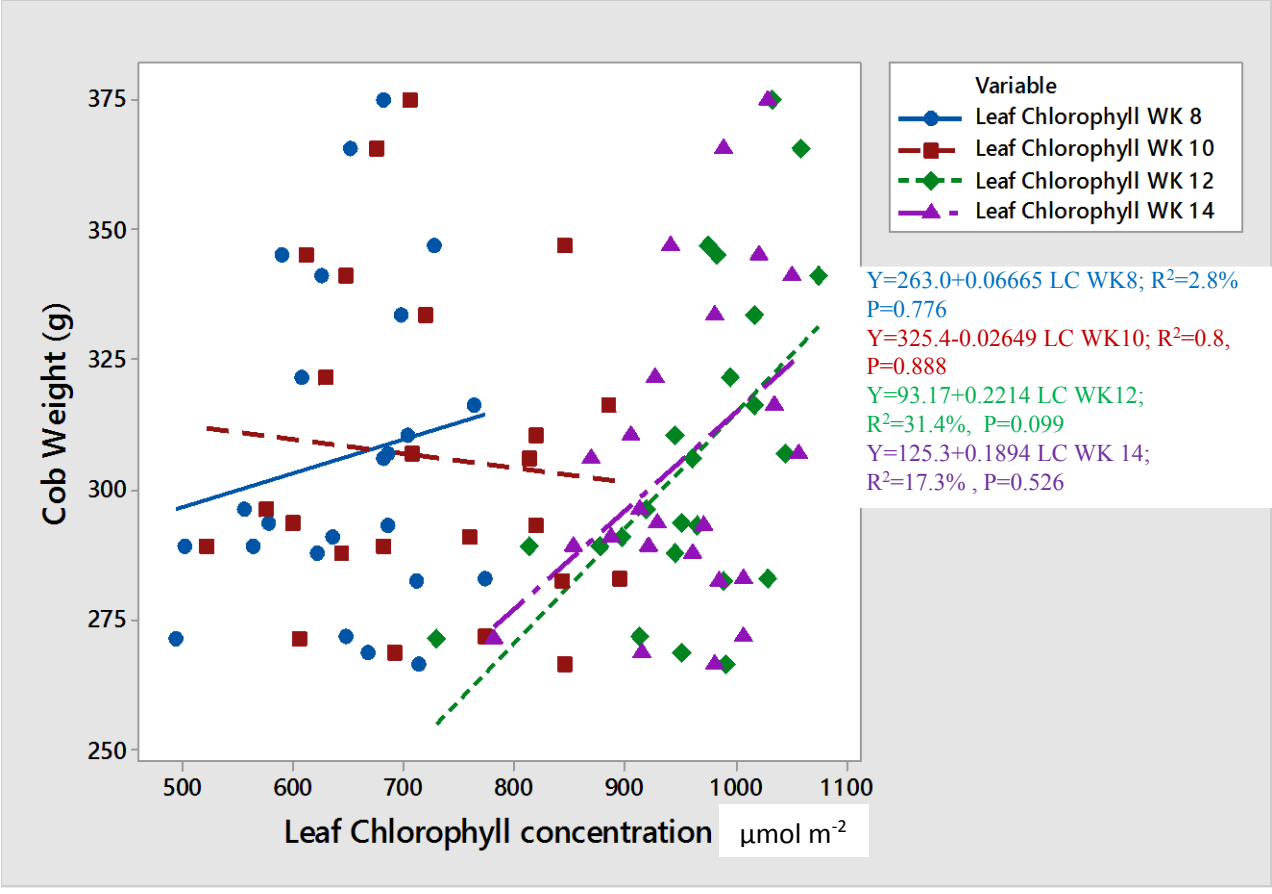

Fig. 5.6: Cob weight of *Zea mays* as influenced by leaf chlorophyll concentration.

Unlike cob weight and leaf chlorophyll concentration relationship, cob weight increased linearly with decreasing PAR interception throughout the period of measurement (Fig. 5.7). The data indicated very strong relationship between these variables (i.e. r = 0.71, r = 0.60 and r = 0.73) for 12 WAP, 14 WAP and 17 WAP respectively). The effect of competition for resources due to high population density can be realized as treatments that recorded highest interception produced low weight cobs. According to Watkinson (1984), yield per plant increases linearly with available space. Again, both treatments with the lowest (T_2) and highest (T_6) plant populations did not experience any significant difference (Table 4.7). This finding may be attributed to the fact that the wider row spacing for T_2 led to partial distribution of PAR from the upper to lower leaves which allowed more radiation to strike the soil surface (as indicated in Table 4.2) and thus reduced the yield (Ottman & Welch, 1989).

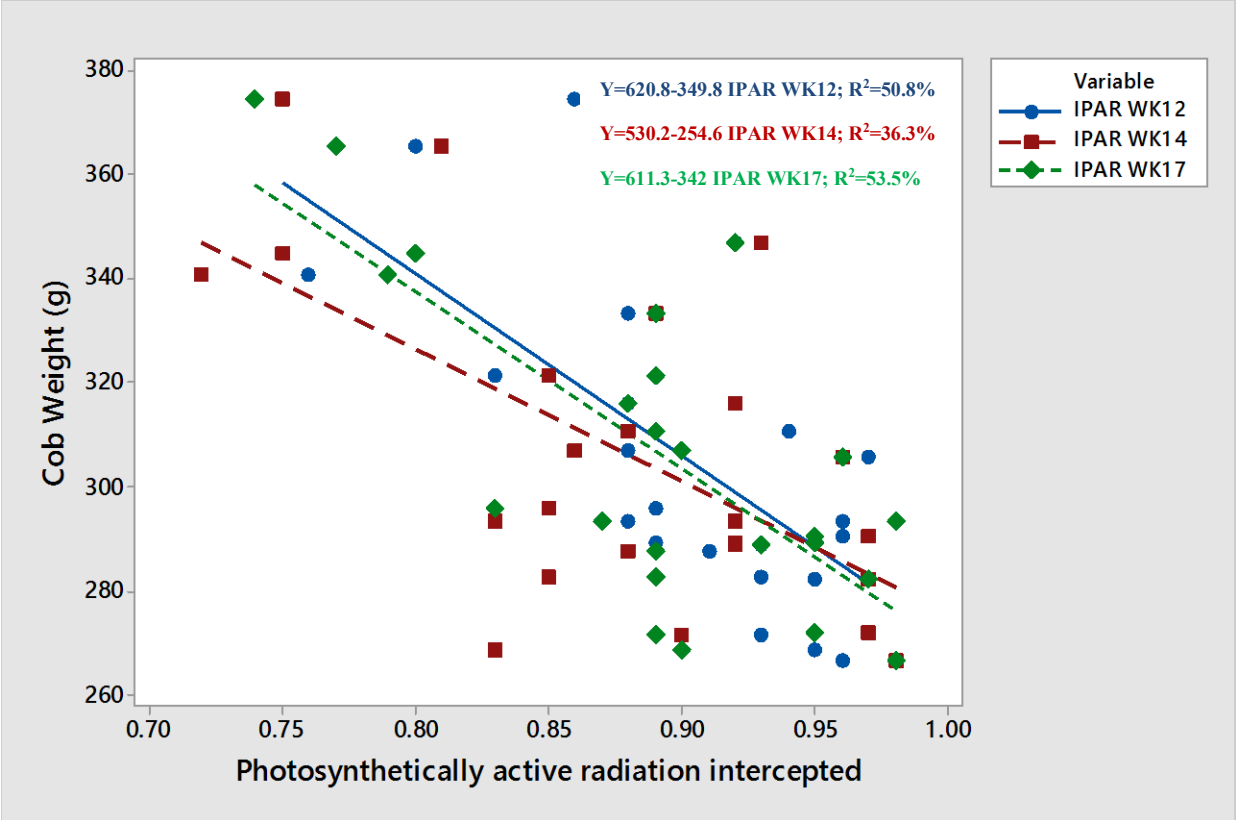

Fig. 5.7: Radiation interception effect on cob weight of *Zea mays*.

5.2.3 Cob length (mm)

There were no significant differences (P<0.058) in cob length between treatments (Table 4.7). The least cob length values were associated with the 0.38m row width whilst the highest values came from the 0.78m row width. Cob length generally decreases with increasing plant population (Gobeze *et al*., 2012; Fanadzo *et al*., 2010; Manan *et al*., 2016).

5.2.4 Number of Kernels/Row

There were no significant differences (P<0.571) in number of kernels/row between treatments (Table 4.7). The mean number recorded was 29.72 with values ranging from 28.98 to 30.65. This was contrary to studies by Sharifi *et al*. (2009) and Abuzar *et al*. (2011) when plant population density significantly affected number of kernels/row.

5.2.5 Number of Kernel Rows/Ear

Several studies have reported different outcomes regarding the effect of row width and intra row spacing on number of kernels rows/ear. Abuzar *et al*. (2011) reported a maximum number of kernel rows/ear (15.44) from 60,000 plants/ha and added that plant population had a significant effect. Mean number of kernel rows/ear was 12.77 and treatment means were not significantly different (P<0.215) (Table 4.7). Similarly, Sharifi *et al*. (2009) reported that the number of kernel rows/ear was not significantly affected by plant population density and according to Elmore and Abendroth (2006) the number of rows/ ear is affected by genetics and growing season stress.

5.2.6 Dry matter (DM) yield (t ha^{-1})

The significant differences ($P<0.001$) in dry matter (DM) yield were due to treatment effects and the interaction between row width and intra row spacing. At same intra row spacing (0.18cm), DM yield for the 0.38cm row width increased by 49.96%. Similarly, 131.3% percentage DM increase was recorded for 0.38cm row width at 0.24m intra row spacing (Table 4.8) which is much greater than the 7% increase indicated by Porter *et al*. (1996). It is evident that DM yield is affected by plant population density (Ferreira *et al*., 2014; Sadeghi, 2012). Again, the interaction between row width and intra row spacing (plant population density) accounted for the observed differences.

Dry matter (DM) yield was found to increase linearly with leaf chlorophyll concentration at 8 WAP ($r = 0.43$) and 10 WAP ($r = 0.66$), indicating a strong correlation between these variables. Sinclair and Horie (1989) reported a strong correlation between leaf nitrogen (N) and rate of carbon dioxide (CO_2) assimilation even though leaf N content of maize is low compared to that of rice (*Oryzae sativa*) and soybean (*Glycine max*). The regression coefficient for 10 WAP was also different significantly ($P=0.006$) from the others (Fig 5.8). However, the pattern changed when an extremely weak ($r = 0.031$) and no correlation ($r = 0.0$) was found to exist between dry matter yield and leaf chlorophyll concentration at 12 WAP and 14 WAP respectively (Fig. 5.8). This observation was probably due to the fact that N uptake almost ceases during grain filling. The finding may be attributed to the critical nitrogen concentration, % N_c (the minimum % N in shoots needed to produce the maximum aerial biomass at a given time) which declines as a function of shoot biomass accumulation (Plénet & Lemaire, 1999).

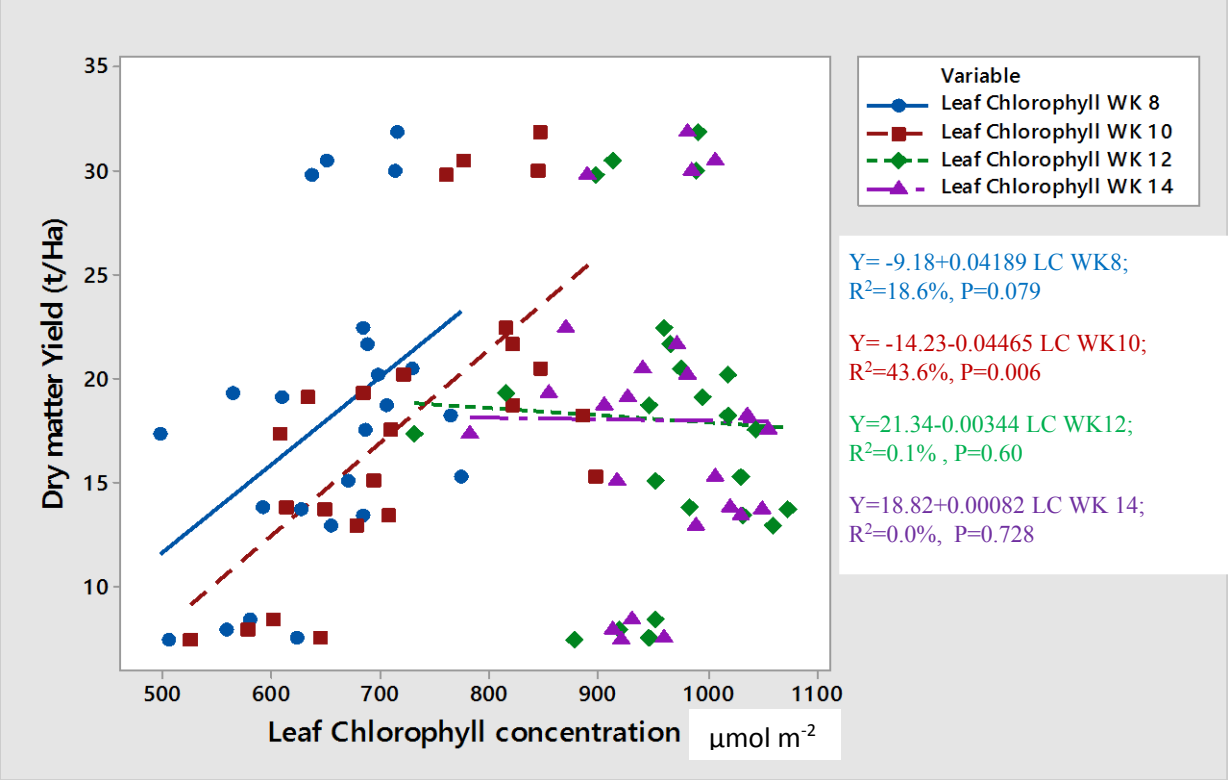

Fig. 5.8: Dry matter yield of *Zea mays* as affected by leaf chlorophyll concentration.

The relationship between DM yield and PAR interception was linear and a strong correlation was established between both variables (i. e. r = 0.48, r = 0.67 and r = 0.63 for 12WAP, 14 WAP and 17 WAP respectively) (Fig. 5.9). These findings affirm the observation of Monteith (1977) that rate of dry matter accumulation is proportional to radiation interception. However, some data points (approximately 11 data points) in spite of intercepting adequate PAR produced yields less than 10 t/ha. This observation might be linked with their low leaf chlorophyll concentration (as indicated in Fig. 5.8) and probably environmental effects such as low temperature.

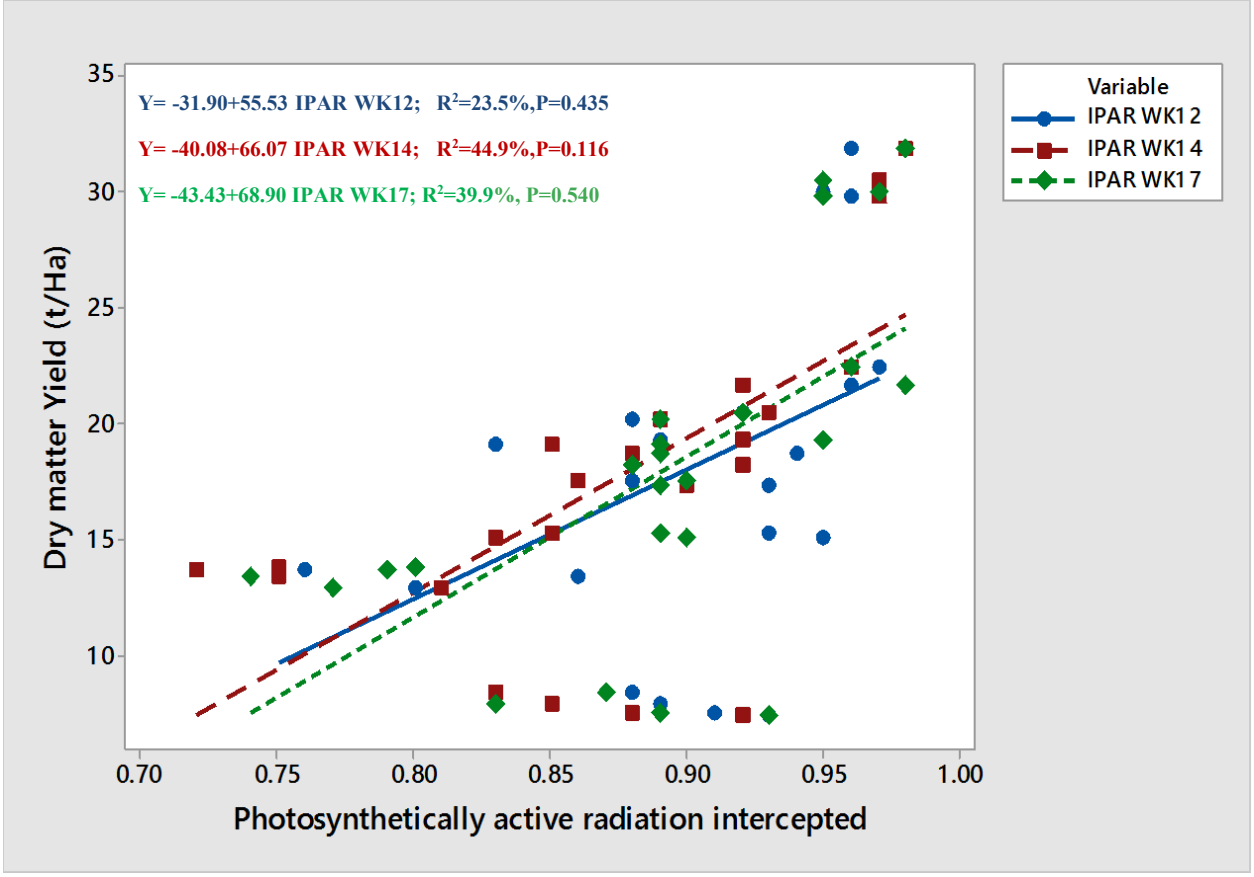

Fig. 5.9: Dry matter yield as influenced by PAR interception at Lincoln University, New Zealand

5.2.7 Grain yield (t ha^{-1})

According to George and Fletcher (2009) plant population had no effect on grain yield. However, the results (Table 4.8) showed that increasing plant population by narrowing row width increased grain yield, an observation which affirms the findings of Widdicombe & Thelen (2002b) and Porter *et al*. (1996). Generally, grain yield for the 0.38m row width was almost twice that of the 0.76m row width. Porter *et al.* (1996) also observed an increase (7%) when maize was cultivated at a narrow (0.38m) row width. Similarly, Douglas *et al*. (1971) reported a grain yield increase of between 8 and 13% when maize was sown in 0.38m rows compared to 0.76m rows. Contrary to these observations, grain yield increased to 78.6% when row width was reduced from 0.76m to 0.38m at same intra row spacing. Similarly, at 0.24m row width, 127.6%

increase in grain yield was recorded when row width was reduced from 0.76m to 0.38m.

Photosynthetically active radiation (PAR) intercepted by the crop canopy also positively affected grain yield. Thus, there was a linear relationship between PAR interception and grain yield was (Fig. 5.10). Grain yield was strongly and positively correlated with intercepted PAR (i.e. r = 0.52, r = 0.72 and r = 0.67 at 12 WAP, 14 WAP and 17 WAP respectively). Increasing plant density increased the absorption of PAR as well as grain yield (Dahmardeh, 2011). The wider row spacing also resulted in partial distribution of PAR from the upper to the lower leaves which allowed more radiation to strike the soil surface and thus reduced yield (Ottman & Welch, 1989). The low grain yield (< 10 t/ha) recorded in spite of the high PAR interception (Fig. 5.10) might again be associated with the low leaf chlorophyll concentration of some sampled leaves also affected DM yield (Fig. 5.9).

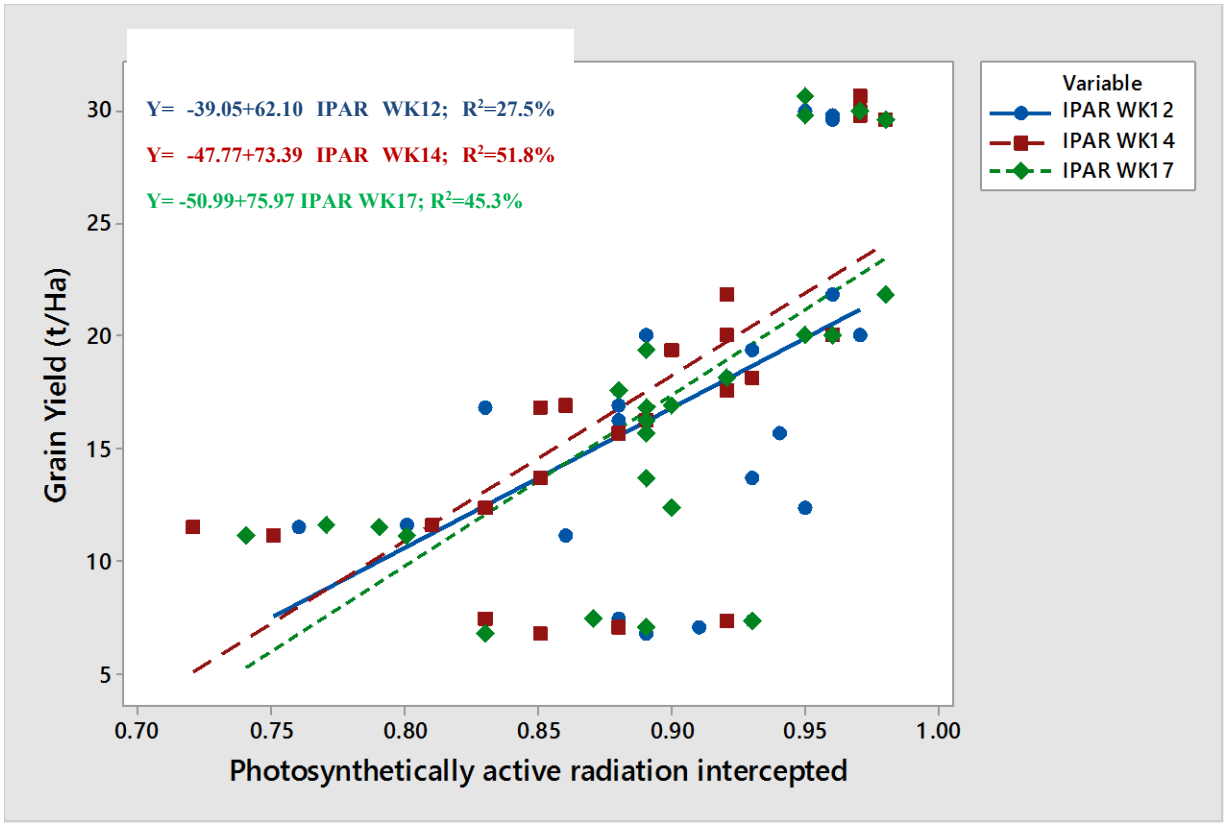

Fig. 5.10: Grain yield of *Zea mays* versus intercepted photosynthetically active radiation.

Leaf chlorophyll concentration also influenced grain yield at 8 WAP and 10 WAP (i.e. $R^2 = 0.11$ and $R^2 = 0.37$ respectively) (Fig. 5.11). However, between 12 WAP and 14 WAP grain yield increased with decreasing leaf chlorophyll concentration (i.e. $R^2 = 0.24$ and $R^2 = 0.05$ respectively). This grain yield-leaf chlorophyll relationship observed may be attributed to the fact that demand for assimilates (especially after silking) to support kernel growth (Tollenaar and Dwyer, 1999) cause N uptake to almost cease. According to Passioura (1976) remobilization of resources from leaf occurs when the demand for resources exceeds supply. This observation also explains N effect on grain yield through the number of kernels initiated (Echarte *et al*., 2004; Jacobs & Pearson, 1991). Andrade *et al*. (2002) established a strong correlation between ear growth and its nitrogen content.

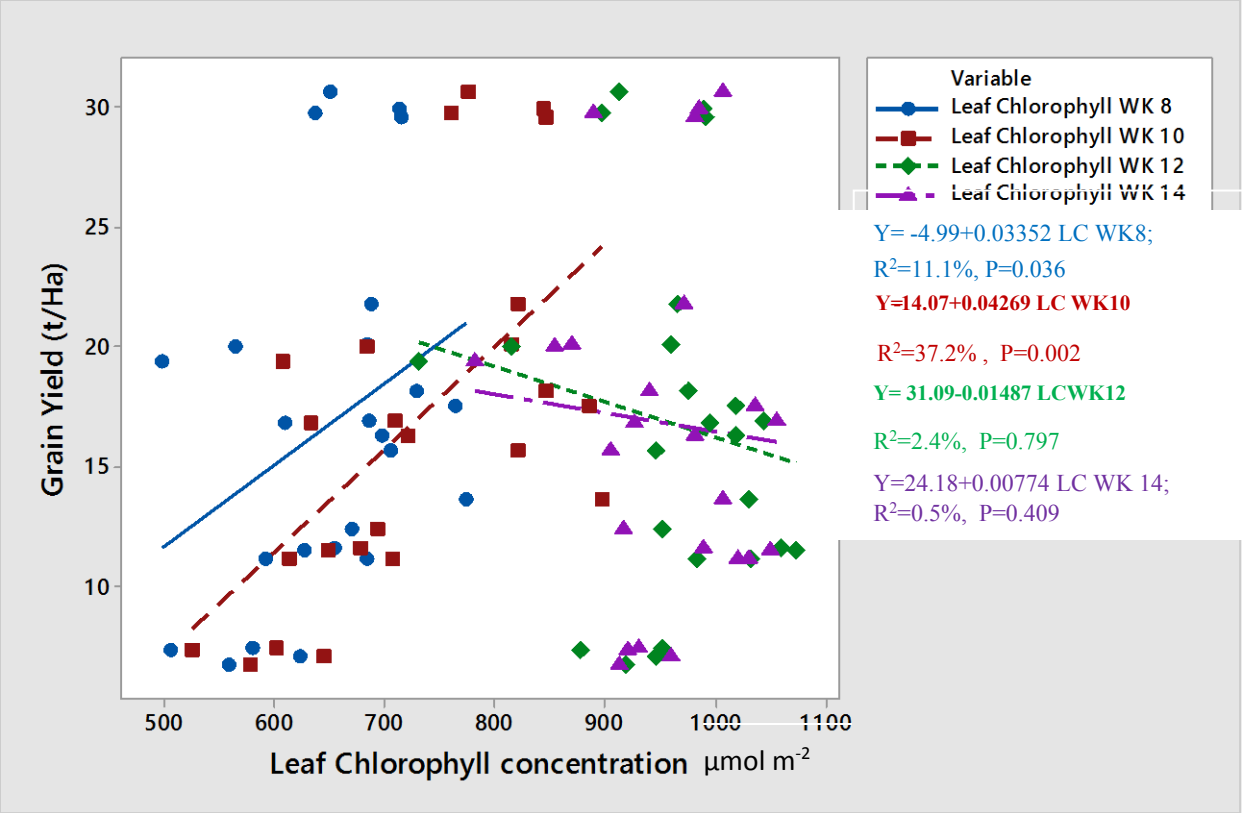

Fig. 5.11: Relationship between grain yield of *Zea mays* and leaf chlorophyll concentration

5.2.8 Stover yield (t ha^{-1})

Stover yield increased with increasing plant population density and the narrow row width (0.38m) recorded 7.7 t ha^{-1} mean stover yield above the 0.76m row width (Table 4.8). The results indicate that stover yield increased linearly with leaf chlorophyll concentration at 8 WAP and 10 WAP (Fig.5.12). The correlation, although positive (r = 0.45), was weak at 8 WAP. However, a much stronger correlation (r = 0.67) was recorded at 10 WAP. Biswas and Ma (2016) recorded similar observations where maize stover increased with increasing N rates. The increasing linear trend changed at 12 WAP and 14 WAP when no correlation was established. This may have been due to the allocation of crop resources especially after silking, when N is remobilized into the kernel (Tollenaar & Dwyer, 1999).

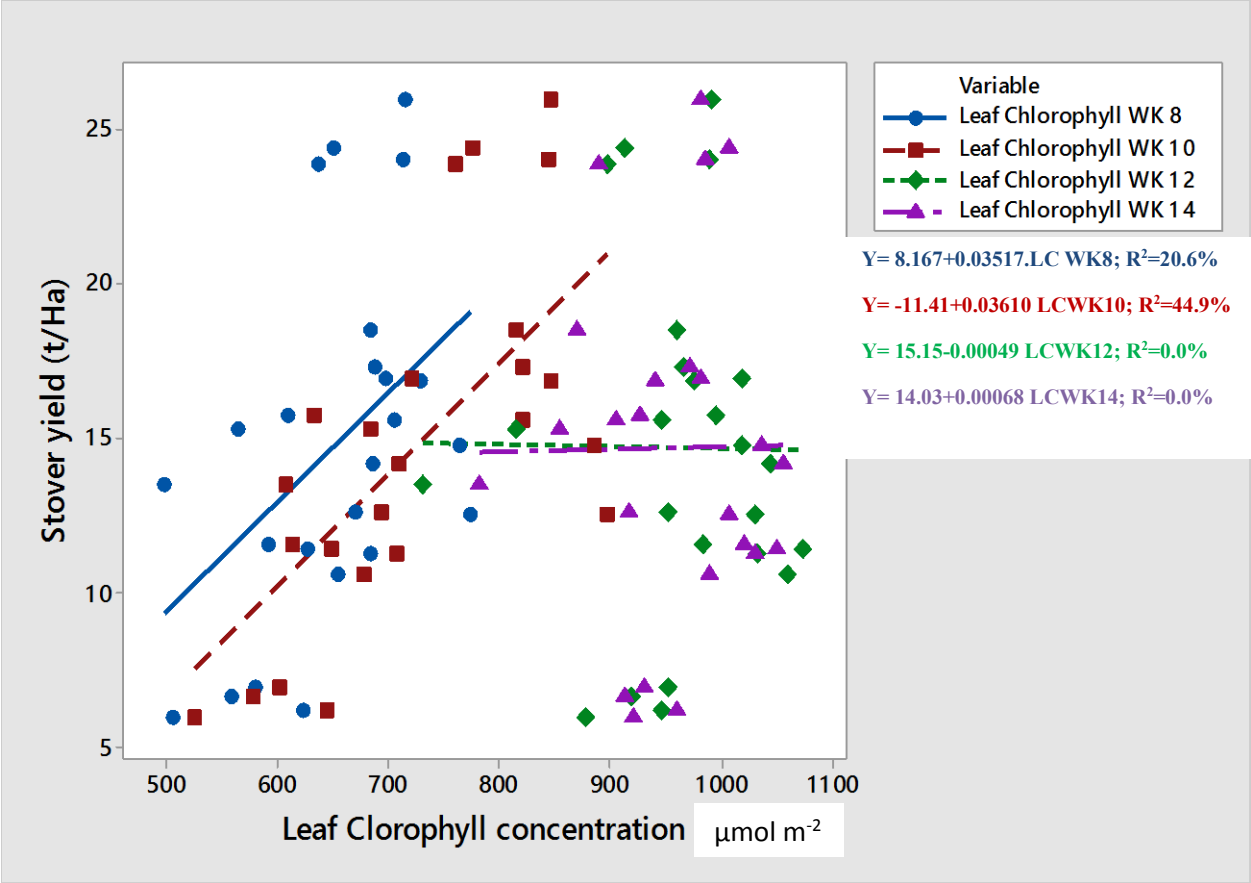

Fig. 5.12: Stover yield of *Zea mays* versus leaf chlorophyll concentration.

Stover yield was found to increase linearly with increasing PAR interception (Fig. 5.13). Thus, stover yield was positively correlated with radiation interception. Although weak (r = 0.472) at 12 WAP, it became stronger at 14 WAP (r = 0.65) and 17 WAP (r = 0.63). These findings correspond with observations made by Ottman and Welch (1989) that narrow row spacings enable crops to intercept more radiation rather than allowing it to strike on the soil surface which leads to increased photosynthetic activity and radiation use efficiency.

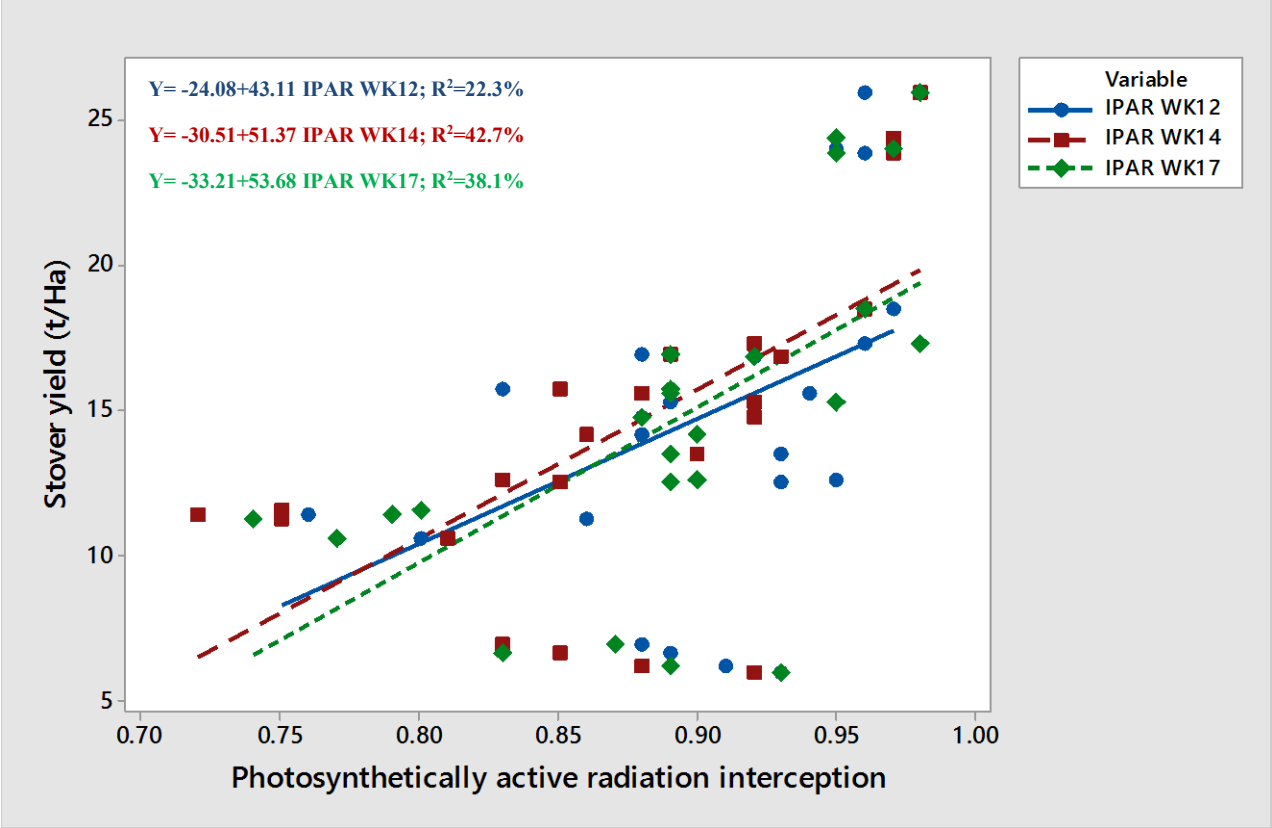

Fig. 5.13: Relationship between stover yield of *Zea mays* and radiation interception.

5.2.9 Forage yield (t DM ha^{-1})

There were no significant differences (P<0.559) in forage yield between treatments (Table 4.8). The mean yields for the 0.76m and the 0.38m row spacings were 33.09 t DM/Ha and 29.93 t DM/Ha respectively. Thus, the 0.76m row width recording a 10.56% increase over the 0.38m row width. This is in line with a similar study conducted by Ramezani *et al*. (2011) where wider row spacings increased leaf and stem fresh weights by 10.4% and 4.7% respectively.

5.3 Effect of row width and intra row spacing on the nutritive value of maize silage

5.3.1 Acid Detergent Fibre (ADF)

Crop row width and intra row spacing had no significant impact on ADF (Table 4.10). The values recorded both at harvest and after fermentation were less than the 23-32% range shown by other researchers (Bal *et al*., 1997; Mahanna, 2000) and confirmed by Ottman and Welch's (1989) finding that planting pattern has no consistent effect on the nutrient concentration in a plant. Studies have also indicated that ADF is negatively correlated with energy and digestibility. Thus, forages with low ADF are desirable and usually have high metabolizable energy (Swift, 2004).

Acid Detergent Fibre (ADF) concentration has been found to increase linearly with increasing plant population density (Stanton *et al*., 2007) and level of maturity at the early stage of the plant (Cherney & Marten, 1982). However, the data available is contrary to the findings of Stanton *et al*. (2007). The highest ADF values both at harvest and that for the silage were recorded by the 0.76m row width with the lowest plant population density (Table 4.10) which also confirms the study of Ottman and Welch (1989). The level of plant maturity cannot also be a contributing factor to the low ADF values recorded because its impact ADF is significant only at the initial stages of the plant but levels off at the later maturity stages.

The low ADF values recorded might be attributed to low environmental temperatures experienced by plants at the early stages, since lignification increases with environmental temperature (Van Soest *et al*., 1978).

5.3.2 Neutral Detergent Fibre (NDF)

Generally, low NDF values were recorded, especially after the ensiling process, and the mean NDF at harvest (46.04%) was close to the average for well-eared corn silage (46%) proposed by the National Research Council (1996). NDF at harvest increased with decreasing plant population density which was contrary to the findings of similar studies which indicated that NDF increases with increased plant population density (Cusicanqui & Lauer, 1999; Stanton *et al*., 2007). The variation in NDF may be attributed to environmental temperatures since temperature contributes to NDF variability at harvest (Crasta *et al*., 1997).

Similarly, the NDF values for silage ranged from 32.60% to 36.60% (Table 4.10). Although they were below the range (38-45%) proposed by Mahanna (2000), they were not too far from the 35-50% range (Hills Laboratories, n.d). NDF is negatively correlated with feed intake and energy uptake (Swift, 2004). This suggests that the low NDF silage will be of high quality and result in a high level of intake. The reduction in NDF of the silage may be attributed to the method of fermentation used as Bossen *et al*. (2008) in a study to evaluate the effect of three fermentation methods on NDF degradation showed that methods of fermentation are very essential in estimating amylase-treated neutral detergent fibre (aNDF) degradation for feed.

5.3.3 Crude Protein

The amount of crude protein in corn silage varies widely (Baah *et al*., 2004) ranging from 7 to 8% (Mahanna, 2000; Wahlberg, 2004), especially when untreated. However, Glover and Mertz (1987) indicated 9-10% as the level of protein in corn. The crude protein content at harvest ranged from 5.68 to 6.39% (Table 4.10). However, it is not uncommon to record < 6.5% crude

protein for corn (Hoffman, 2015). The Northeast Dairy Herd Improvement Association (1995) recorded 5.9 to 10.3% crude protein levels for 17,358 maize samples analyzed.

The mean crude protein of the silage (7.84%) was 29.16% higher than the mean crude protein at harvest (6.07%) and this could be attributed to the fermentation process. According to Baah *et al*. (2004) soluble crude protein is increased by the ensiling process, due to the production of nitrogenous compounds such as ammonia and amines.

The row width and intra row spacing effect on crude protein was inconsistent, contrary to the findings of Cox and Cherney (2001) that crude protein decreased with increasing plant population density. However, it supports the findings of Ottman and Welch (1989) that planting pattern has an inconsistent effect on plant nutrient concentration.

5.3.4 Metabolizable energy

Metabolizable energy (ME) at harvest ranged from 9.80 to 10.83 MJ/kg DM, whilst that of the silage ranged from 11.50 to 12.03 MJ/kg DM (Table 4.10). The ME values recorded both at harvest and after fermentation indicated increased quality. Millner *et al.* (2005) indicated ME range from 10.3-11.3 MJ/kg DM. According to Mahanna (2000) the Metabolizable Energy of good quality silage is ≥ 10.8 MJ/kg DM. Kirkland *et al*. (2005) in a study also showed that the ME of maize (with/without inoculants additive) ranges from 9.89 to 10.96 MJ/kg DM. The mean ME of the silage was 13.6% above that of the original crop at harvest. This is contrary to what Charmley (2000) regarded as a major disadvantage (i.e. a reduction in feeding value of the resultant forage) associated with silage. According to McDonald *et al*. (1973) changes in composition of a crop

which occur during the ensiling process result in an increased gross energy of the silage than that of the crop prior to ensiling.

5.3.5 Dry matter digestibility

The mean dry matter digestibility (DMD) at harvest and after fermentation (silage) were 71.11% and 72.21% respectively (Table 4.10). According to Wilkins (2013) the dry matter digestibility of a crop before silage is similar to that of the crop after ensiling. The slight increase recorded was likely due to the increase in structural carbohydrate during ensiling which was compensated for by a small increase in digestibility (Demarquilly, 1973).

CHAPTER SIX

General discussion and conclusions

6.1 Effect of row width and plant population density on yield and silage quality

The yield components assessed included green leaves:dry leaves, cob length, cob weight, cob diameter, number of kernels per row, number of kernel rows per ear, grain, dry matter and stover yield. However, other growth parameters such as plant height stem girth and number of leaves per plant were also assessed.

Row width and plant population density did not have any significant effect on plant height (Table 4.3), number of leaves per plant (Table 4.5), green leaves:dry leaves (Table 4.6), cob diameter, cob length, number of kernels per row, number of kernel rows/ear (Table 4.7) or forage yield (Table 4.8). On the contrary, grain, dry matter and stover yields (Table 4.8), cob weight (4.7) and stem girth (Table 4.4) were significantly affected by row width and plant population density. The 0.38m row width recorded higher DM, grain and stover yield compared to the 0.76m row width. Thus, grain, DM and stover yield increased with increasing plant population density (Ferreira *et al.,* 2014; Porter *et al.,* 1996; Widdiecombe & Thelen, 2002b). Percentage grain yield increases of between 78.6% and 127.6% were recorded for the 0.38m row width which was contrary to the finding of Douglas *et al.* (1971). The nutritive values of silage did not record any significant differences.

6.2 Effect of radiation interception on yield

Generally, the narrow (0.38m) row width increased radiation interception (Table 4.2). The stem girth (Figs. 5.1, 5.2 & 5.3), cob diameter (Fig. 5.4) and cob weight (Fig. 5.7) increased with decreasing radiation interception, indicating the negative impact of increased stress level due to increasing plant population (Baghdadi *et al.,* 2012; Adeniyan, 2014). According to Watkinson (1984), yield per plant increases linearly with available space. On the contrary, DM yield increased with increasing radiation interception (Fig 5.9), confirming the study by Monteith (1979) that the rate of DM accumulation is proportional to radiation interception.

Increasing radiation interception also increased grain (Fig. 5.10) and stover (Fig. 5.13) yield because the wider (0.76m) row width allowed partial distribution of PAR from the upper to the lower leaves and more radiation to strike the soil surface thereby reducing yield (Ottman & Welch, 1989). Generally, the effect of row width and plant population density on leaf chlorophyll concentration was inconsistent. The mean leaf chlorophyll concentration of the 0.38m row width was higher at 8 WAP and 10 WAP whilst the 0.76m row width recorded higher mean chlorophyll concentration at 12 WAP and 14 WAP.

6.3 Influence of leaf chlorophyll content on yield

Cob diameter (Fig. 5.5) and cob weight (Fig. 5.6) increased with increasing leaf chlorophyll concentration though the correlation was weak. There was a strong correlation between DM yield and leaf chlorophyll concentration at 8 WAP and 10 WAP. However, a weak and no correlation between leaf chlorophyll concentration and DM yield were observed at 12

WAP and 14 WAP (Fig. 5.8) due to the critical N concentration which declines as a function of shoot biomass accumulation (Plenét & Lemaire, 1999).

Leaf chlorophyll concentration also affected grain yield positively at 8 WAP and 10 WAP. However, grain yield decreased with increasing leaf chlorophyll concentration (Fig. 5.11) between 12 WAP and 14 WAP due to the demand for assimilates to support kernel growth (Tollenaar & Dwyer, 1999). The resources in the leaf are remobilized when the demand for resources (assimilates) exceeds supply (Passioura, 1976). The relationship between stover yield and leaf chlorophyll concentration was similar that of grain yield and leaf chlorophyll concentration (Fig. 5.12).

6.4 Conclusions

Based on the findings of this study, the following conclusions can be drawn;

- Although plants may have the same population density, the interaction between row width and intra-row spacing had no significant effect on radiation interception and cob weight.
- Increasing plant population increased the overall interception of radiation and yield (grain, DM and stover) per unit area. However when plant population increased, yield per plant declined due to competition between plants.
- Plant population when increased affects positively the leaf chlorophyll concentration in the initial weeks after planting due to a higher NUE. However, leaf chlorophyll concentration decreased with increasing plant population at the latter stages of maize growth and development due to competition between plants.

- At constant intra row spacing, Grain and DM yield for the 0.38m row width was almost twice or more compared to that of the 0.76m row width.
- Row width and plant population density did not have any significant effect on nutritive value of maize silage.

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Appendices

Appendix I: Total amount of water (mm) received by the crop during the period of study (Nov., 2015 – April, 2016)

Source	Months						Total (mm)
	Nov	Dec	Jan	Feb	Mar	Apr	
Irrigation (mm)	15.00	20.00	-	80.00	20.00	-	**135**
Rainfall (mm)	1.02	41.15	75.44	20.83	53.59	4.57	**196.6**

Appendix II: Soil tests results for the Horticultural Block (11) with the recommended soil nutrients level for maize (Steele, 1984).

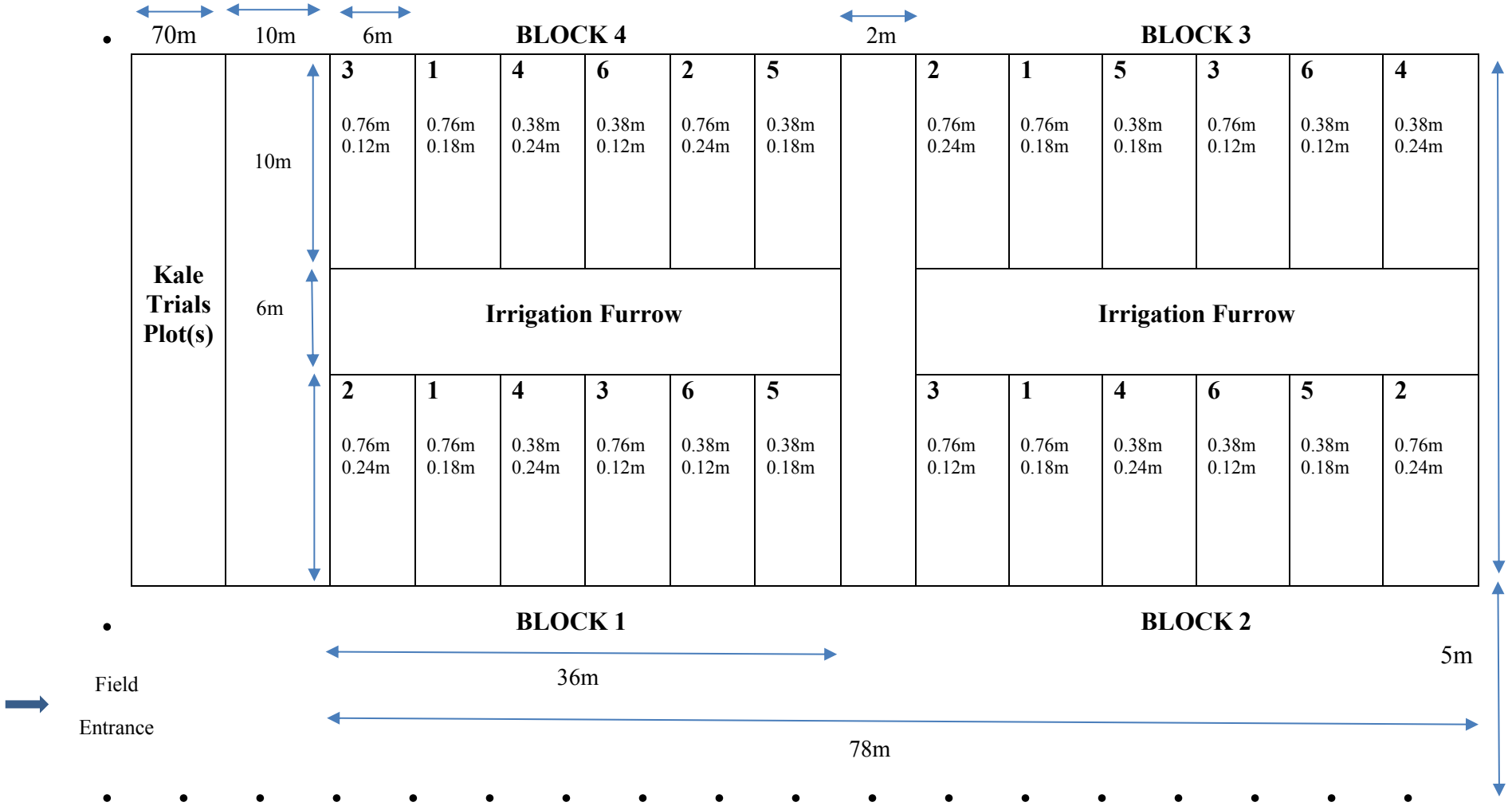
Nutrient	pH	N^1	N^2	P^3	Ca	Mg	K	Na
Unit	-	kg ha^{-1}		mg/L	QTU			
Results	5.7	81	49	17	10	21	5	11
Recommended	5.8-6.3	-	-	14-22	-	5	>5	-

[1] Available N (0.15m depth) [2] Mineral N (1.0m depth) [3] Olsen P

Appendix III: Mean monthly climatic conditions during the period of study (November, 2015 – April, 2016).

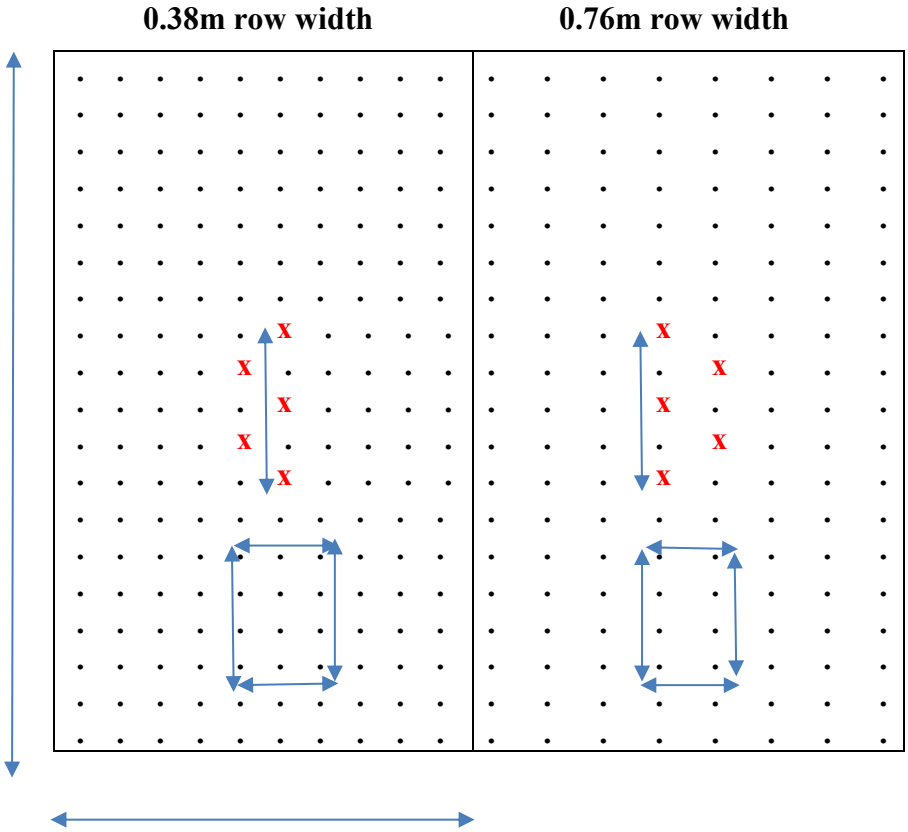
Month(s)	Temperatures (ºC)	Relative Humidity (%)	Wind speed (mph)
November	Max= 9, Min= 3 6	86	8.5
December	Max= 13, Min= 6 9.5	83	6.7
January	Max= 14, Min= 7 10.5	85	7.2
February	Max= 17, Min= 8 12.5	83	7.2
March	Max= 13, Min= 7 10	86	6.5
April	Max= 10, Min= 4 7	87	5.8
Total	**55.5**	**510**	**41.9**
Mean	**9.25**	**85**	**6.98**

Appendix IV: Field layout



KEY: • Hedging plants/Wind breaks

Appendix V: Diagram illustrating harvested area/ plot and sampled plants



KEY: $1m^2$ area harvested for forage yield assessment and later fermented for silage quality analysis.

5 contiguous plants sampled for yield assessments and NIR on maize nutritive at harvest.

x Sampled plant(s) for growth parameters.

Appendix VI: Sampled plants divided into various components for yield assessment

Sampled maize divided into cobs, dried and green leaves.

Stems of sampled maize plants to be processed for oven drying.

Appendix VII: PVC silos used for the silage fermentation and sampling of samples

a)

Silage samples in PVC pipes sealed with cap and gaffer tape

b)

10-15cm top layer of silage taken off.

c)

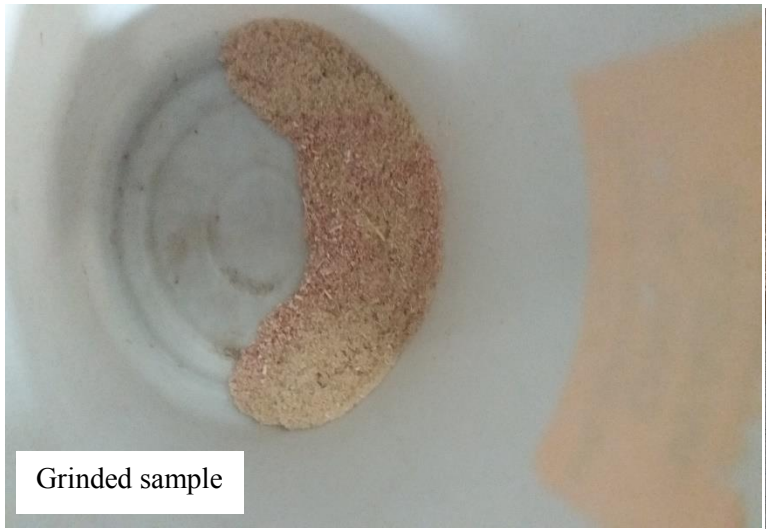
Silage samples taken from middle of the silo

d)

Appendix VIII: Grinding machine and samples for grinding and NIR analysis

The Yeoman Major grinder

Dried cobs and stems to be grinded



Grinded sample

Grinded silage samples for NIR analysis

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